On the Existence of a

Family of Ideal Aircraft Configurations

by

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Abstract

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The overwhelming majority of all subsonic aircraft are based on the same configuration. However, this basic layout of wings and fuselage is perhaps not ideal in terms of flight efficiency. Assuming that better configurations may exist, alternatives have always been explored. Ever since the developmental priority has been focused on flight efficiency, large investments have been specifically committed to such research. If superior configurations do exist, as many results suggest, these should be implemented as a matter of urgency given the enormous environmental pressure imposed by the fast-growing aviation industry. However, until now, no consensus has been reached on which alternative to implement.

To offer an alternative perspective on the old question of what an aircraft should look like, the aircraft design space was organised into families of configurations. For this purpose, a hypothetical ideal wing was introduced as a common ancestor in an imagined evolution of progressive complexity to organise configurations into families of different morphology. This approach allows for comparative evaluation at configuration level applying a new quantitative figure of merit without yet requiring exhaustive numerical optimisations. It was then hypothesised that a single family of configurations ought to be ideal for the majority of flight objectives, given that the shape for best efficiency must be a matter of physics alone, and given that typical flight objectives have much in common.

While the current dominant aircraft configuration represents such a single family among the multi-wing arrangements, evaluation of its quality in terms of the new quantitative metric supports the widely held suspicion that it has avoidable deficiencies. Furthermore, within the design space, there exists a family of configurations among the single-wing arrangements that might be free of these deficiencies. This alternative has not been implemented in human aviation, leaving three high-level questions unanswered: (i) Could the configuration be implemented in aviation? (ii) How would it best be implemented? (iii) What improvement of flight efficiency can be gained by its implementation?

The first question was explored in this research by qualitative evaluation of the handling qualities of the alternative wing layout and method of control by radio-controlled and full-scale tethered flight under direct human control. Other predicted flow effects around the alternative body arrangement were evaluated in wind tunnel tests.

In conclusion, the notion of a single family of ideal configurations appears to be meaningful. Furthermore, because no practical hurdles have yet been found, the proposed arrangement seems to be a viable alternative to the current dominant configuration. Therefore, it seems justifiable to explore its potential further by dealing with the next two questions in future work.

Acknowledgements

The work consolidated here has a long history and many people have made significant contributions. While it is not the purpose of this document to record this history, it is ultimately not enough to merely list the contributors as is done on this page. Therefore, a separate document is dedicated to the history of this project in which due acknowledgement is given. In that work, acknowledgements are cast into the story of the project to highlight the important personal interactions with the people listed here. The list offered here (more or less in order of appearance) is inevitably incomplete and I hope to be forgiven by the many not mentioned here despite their important contributions. Because the list of students who have been involved through their research and design projects or practical training work, would be too long, their names are excluded but their contributions are collectively gratefully acknowledged here as well. Particularly memorable are the students who visited for six-month full-time participation from Germany, Switzerland, France, Holland and Italy.

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For his participation as design partner, I thank my brother Dieter. For their permissions, support and patience, I thank my parents, and especially my wife, Barbara, and for his awakening enthusiasm on this topic, our son, Evan.

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Chapter 1

Introduction: Background and Overview

1.1 Background

While the phenomenon of flight has always been observable, for the longest part of history, humankind remained without the art of flight. Only the last two centuries saw aviation emerge and grow into perhaps the most influential sector of the transport industry, with most economic activity taking place in the domain of subsonic, fixed-wing flight. With the principal objective of transporting passengers and cargo, air traffic is still growing at almost 5% per year [1]. Not only did aviation mobilise humanity on a global scale, but it also adversely changed the global atmosphere and tranquillity. At 11% of all transport energy, the aviation industry alone burned about 0.7 megatons of fossil fuel every day in 2006 [2], depositing problematic emissions of combustion into the upper atmosphere [3]. A complex mix of constituents involved in global shielding and global warming contributes significantly to global climate change [1, 2]. This industry still relies exclusively on high-grade refined fossil fuels as an on-board energy store of high energy density for the combustion-based propulsion systems. As aircraft burn a substantial portion of their fuel only to carry the fuel, this sector of the industry is most sensitive to the issue of energy efficiency. On a long-haul flight, the payload may be as little as 8% of the take-off weight with fuel (45%) weighing almost the same as the empty aircraft (47%). With dwindling fossil fuel reserves, the steep growth in demand and the detrimental impact on the environment, the industry is confronted with an environmental and economic crisis. Therefore, it is crucial that all aircraft operate at the best flight efficiency to avoid unnecessary fuel consumption.

The aircraft that accomplishes a specific transportation act with the lowest fuel burn is that with the lowest integrated thrust over the distance of the mission. Since thrust primarily balances drag, flight efficiency is related directly to total aircraft drag. In this context, the primary task of the aircraft designer is to find the aircraft shape and structure that minimise the integrated drag for a given set of economic choices, safety considerations and state of technology. Only designs based on the best basic arrangement or configuration of wings, controls and payload volume can, in principle, be refined towards the optimum. If this basic aircraft arrangement is not ideal, no effort of refinement can reach the best possible flight efficiency.

1.2 Problem of the Current State

The problem is that the ideal arrangement for a given flight objective is not known with certainty. It is thus conceivable that the lowest fuel consumption may not be achievable with the aircraft arrangement of the current art. Already by the middle of the previous century, aircraft development had converged onto a single basic arrangement or layout and the aviation industry became firmly entrenched in this dominant configuration. Evidently, there remains doubt whether this basic arrangement is best when compared with practicable alternatives, as confirmed by the continued explorations of alternatives throughout the history of aviation. In the last few decades, with flight efficiency receiving higher priority in aircraft development, such explorations have escalated to significant multinational initiatives under programme names such as NACRE (New Aircraft Concepts Research) [4], ERA (Environmentally Responsible Aviation) [5] and Clean Sky Joint Undertaking [6]. These initiatives typically investigate alternatives for specific applications within the domain, often focused on large aircraft, and the conclusions may therefore be equally specific.

Despite multidisciplinary optimisation tools having achieved useful maturity, it seems that such tools have not yet been applied to find the best aircraft configuration by rigorous computational optimisation. Many optimisation exercises still operate within explicit configuration constraints, so that the entire configuration space is not reachable in every search. The focus is often on complex trade-offs and refinement of details within a given configuration and comparison at configuration level remains beyond the repertoire of the typical optimisation tool.

Any conclusions derived from theoretical simulation alone, lack the reliability that full implementation and refinement in operation would offer. Recent experimental explorations have been limited to sailplanes or scale models with alternatives for large aircraft never having been tested at full scale.

Nonetheless, the outcomes of such research would be of general interest if these could convincingly demonstrate that superior alternatives do exist, even in a limited field of application. Though several alternatives have been proposed, the industry is reluctant to take the risks to change. Therefore, there is still no reliable answer to the oldest question in aviation: *What should an aircraft look like?*

1.3 Challenge

The challenge is thus to find a measure to help decide whether further searching is necessary and if it is, what to search for. If a convincing case can be made that the current dominant arrangement is most likely the ideal candidate, the industry should continue refining it for all typical applications without the distraction of searching for alternatives. On the other hand, if superior configurations do exist, priority should be given to the exploration of alternatives. The next challenge would then be to reach a consensus on the basic shape of the ideal aircraft before embarking on the rigorous development of details by simulation and experiment.

1.4 Aims and Objectives

This research had three main objectives. The *first part* involved an analysis of the configurational design space to allow comparative evaluation of different configurations by means of clearly defined metrics, and without requiring optimised designs for all compared alternatives. From this emerged the hypothesis that only one family of configurations should be ideal for the majority of all flight objectives. Comparative evaluation suggested that the current dominant configuration might not be a candidate for this ideal configuration. The configuration that might be a candidate has not yet been fully explored. This raised the question of whether it could work in practice.

The second part was an investigation of the proposed candidate to test whether a human pilot could fly an aircraft of this arrangement. The focus was on the handling qualities and stability characteristics of an arrangement and a method of aircraft control that could continue to enable flight at best efficiency. This was an essential early step, because if the handling characteristics were problematic, then further developments would perhaps be futile.

The *third par*t was an investigation of the aerodynamic properties of a novel fuselage arrangement. The objective of this experimental investigation was first to confirm whether the fuselage of the current art imposes a fundamental penalty on flight efficiency and second, to test whether the proposed alternative could avoid this penalty.

The aim was to offer a new perspective on the old question with the ultimate objective to allow flight with better efficiency in all applications. While such a lofty objective was never expected to be reachable in a single thesis, at least the first steps have been taken to test whether further steps along this line of inquiry are called for.

1.5 Thesis Structure

In line with the three project aims, the thesis is presented in three parts. Chapters 2 and 3 provide a historical overview. Chapter 4 discusses the philosophical analysis of the aircraft design space. The metrics required were developed in detail in a publication which appears as Appendix A.

Chapter 5 describes the flight experiments with supplementary details of experimental aircraft and test facilities presented, in Appendices E to I. Chapter 5 also provides the numerical investigation of the proposed configuration with its resulting publication presented as Appendix B.

Chapter 6 describes the third independent body on work of the wind tunnel experiments with its resulting publication presented as Appendix C.

Chapter 7 summarises the features of the proposed configuration with reference to a patent that resulted from this work. The patent itself appears in Appendix D. In summary and in conclusion, Chapter 8 briefly recommends a strategy of implementation from which useful steps for future work can be taken.

The main body of the thesis outlines the principal features and arguments and can be viewed on its own, but many technical details, useful elaborations and additional references are presents in the appendices.

1.6 Definitions and Limits

1.6.1 Flight Efficiency

In this research, flight efficiency is related to the energy required to carry a certain payload m_{PL} over a certain distance d in a chosen time t. Together, d and t reflect the flight speed V of choice in which an operator already considers the economic implications of time so that the notion of flight efficiency implicitly takes care of such operational considerations. Given that the energy of flight is predominantly invested in doing work against total aircraft drag, flight efficiency is linked directly to drag. On a comparative basis, with propulsion efficiency, t, d and m_{PL} being the same, the aircraft which achieves the transportation act with the smallest integral of work against drag along the mission will have the best flight efficiency for requiring the smallest investment of energy to achieve the flight objective.

For the case of a glider, where the choice of wing loading might be deliberately changed according to the expected atmospheric conditions, one may prefer to consider the lift L to drag D ratio (L/D) as the metric for efficiency. Even then, for a given lift L and speed V of choice, the absolute drag D remains the parameter that needs to be minimised for best efficiency.

1.6.2 Aircraft Configurations

The term *aircraft configuration* refers to the *basic arrangement* of the lifting devices, the devices for stability and control and the arrangement by which volume is provided for the payload and other bulky elements of the flight apparatus. To allow comparison of powered and unpowered aircraft at configuration level, the arrangement of the propulsion system is not considered part of the basic aircraft configuration, but rather as a further elaboration imposed upon it or integrated into it. This then allows consideration of externally added, integrated, retractable or detachable propulsion systems. During the design process, this basic arrangement lays out the topology for which the detailed shape must be designed. During operation, it forms the basis from which in-flight adaptations are derived (such as undercarriage extension or aerofoil modifications by high-lift devices), without the basic arrangement being changed. As an example of a configuration-level description, when comparing a typical sailplane with a typical airliner, one finds that both employ a single central main wing with their centres of pressure close to the aircraft centre of gravity. Both employ secondary tail wings for balance, stability, control and damping, placed at the rear end of a single central fuselage. The fuselage serves as the container for the payload, elongated to the rear to hold the tail wings and to the front for purposes of mass balance. In this research, their basic arrangements are therefore considered to be the same even though their details of design are vastly different. Even variants in the arrangement of the tail wings and the shape, the posture and the vertical positioning of their main wings are considered as variants of the same basic arrangement.

1.6.3 Domain under Consideration

Since the aircraft design space, in general, includes all types of flight, it was necessary to narrow it down to the domain of flight based on dynamic lift. This portion of the design space excluded ballistic and buoyant flight and it was further narrowed down to exclude drag-based flight and flight based on propulsive lift and rotorcraft. In terms of the dynamic pressure, the domain was limited to subcritical flight. In short, this work considered the domain of fixed-wing, subsonic, heavier-than-air flight.

In terms of size and mass, no upper limit was applied. The lower limit would be in the region where dynamic lift became comparable in magnitude with the viscous forces. Thus, any object of which one could observe gliding flight with a glide angle of more than unity might still be considered within the domain. Therefore, the domain included all birds and bats, many insects, even certain seeds.

1.7 Summary of Contributions

1.7.1 Ideas and Findings

The following summarises ideas and findings, which may contribute towards the main question concerning aircraft configurations:

- **Aircraft Design Space Organised at Configuration Level**

To organise the aircraft design space into an imagined evolutionary family tree, the notions of the *flight objective,* the *ideal wing*, *wing density* and the *inflation factor* were developed. This allowed the mapping of configurations for qualitative comparisons without requiring rigorous design.

- **Notion of the Family of Ideal Aircraft Configurations Proposed**

Based on the imagined evolutionary family tree, the notion of the *ideal configuration* and the hypothesis of the *family of ideal configurations* were introduced. Based on the notion that a single evolutionary line of development should be suitable for the majority of flight objectives, the configuration based on the best protoflyer and implementing the best inflation strategy should be ideal for all typical aircraft designs. If this notion was to be accepted as meaningful, it could have significant implications for aircraft development.

- **Current Dominant Configuration Evaluated**

Viewing the current dominant configuration in the organised design space as the obvious candidate for the proposed family of ideal aircraft configurations allowed for qualitative comparative evaluation. The outcome strongly supported the widely held idea that better configurations might exist and that a step change to another configuration is necessary before the best flight efficiency can be achieved. While this view has already been widespread, here it was advanced from an alternative perspective, grounded in rigorous first principles.

- **Alternative Protoflyer and Inflation Strategy Proposed**

By viewing aircraft as evolving from an ideal protoflyer by inflation, a single family was revealed, which seemed to qualify as a candidate for the proposed family of ideal configurations. This candidate was proposed as an alternative that should be considered for all future aircraft designs in which flight efficiency will be important.

Proposed Protoflyer and Inflation Strategy Tested

The proposed configuration was tested for suitability in the field of human aviation. It was found that this aircraft arrangement and the proposed means of control could meet the basic handling requirements for flight under control by an unassisted pilot. In separate tests, the defining features required for the proposed inflation strategy, a fuselage trailing edge on a body of lower fineness ratio, were tested and found to confer the predicted advantageous effects.

- **Implementation Strategy Proposed**

The aviation industry is firmly entrenched in the current dominant configuration and a step change, if necessary, is unlikely to come from the main sector of the industry. Therefore, it is proposed that a step change could be feasible if experience first matures in sectors of aviation of low economic risk. The free-flight model, the radio-controlled model and the sport of gliding may play an important role in maturing the ideas proposed in this research.

1.7.2 Resulting Publications

In partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Mechanical and Aeronautical Engineering at the University of Pretoria, the following three publications have been submitted as direct contributions from this work by this author with his supervisors (at the time) as co-authors:

- R. J. Huyssen, E. H. Mathews, L. Liebenberg, and G. R. Spedding, "On the Wing Density and the Inflation Factor of Aircraft," *The Aeronautical Journal,* 2016.
- R. J. Huyssen, G. R. Spedding, E. H. Mathews, and L. Liebenberg, "Wing-body Circulation Control by Means of a Fuselage Trailing Edge," *Journal of Aircraft,* 2012.
- R. J. Huyssen as the inventor and the University of Pretoria as the applicant, "The Gull-Wing Patent" Patent, South Africa, 2019.

The following publications resulted from master's projects for which this author served as co-supervisor:

- D. S. Agenbag, N. Theron, and R. J. Huyssen, "Pitch Handling Qualities Investigation of the Tailless Gull-Wing Configuration," *Journal of Aircraft,* 2009.
- S. Meintjes, R. Huyssen, and N. Theron, "Comparison of Crash Response with Different Occupant Support Concepts," *Aircraft Engineering and Aerospace Technology,* 2004.

1.7.3 Conference Presentations

This author presented elements of this work at the following conferences:

- R. J. Huyssen and C. P. Crosby, "The Development of a High-Performance Composite Hang Glider," OSTIV Congress, New Zeeland, 1995.
- R. J. Huyssen and A. Groenwold, "On Tailless Flight: Lessons Learned from the Exulans," OSTIV Congress, South Africa, 2001.
- R. J. Huyssen, "Downwash Control by Means of a Fuselage Trailing Edge," IASSA, South Africa, 2015.
- R. J. Huyssen, "About the Optimum Aircraft Configuration," AeSSA, South Africa, 2018.
- R. J. Huyssen, "Testing the Natural Dominant Configuration for Aviation," AeSSA, South Africa, 2019.

1.7.4 Awards

The following awards were received by this author during the course of this work:

- Gold Award in 'AVI Awards 2016' at the African Aviation Innovation Summit.
- South African Department of Trade and Industry award for 'Most Innovative THRIP Project 2002'.

1.8 Closing Remark

As the questions at the core of this thesis are too big, a comprehensive answer should not be expected from this preliminary investigation. Not even the collective efforts of other experts throughout history have yet achieved this goal. Much work remains, and many others will have to contribute to further develop the ideas presented here. However, the conclusions so far are potentially far-reaching and strongly suggest that this line of inquiry should be continued.

An aircraft configuration different from the current dominant configuration has been outlined, it has been demonstrated in flight by an unassisted pilot and it may be ideal for the majority of flight objectives. However, this work does not yet propose answers to the next big questions:

- How would this configuration best be applied in its detail?
- How much better could the efficiency be for any specific implementation?

These questions are worthy of further investigation.

1.9 References

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Chapter 2

Road to the Current Dominant Configuration

2.1 Introduction

This chapter traces the timelines of the development of the current dominant aircraft configuration in the light of the prevailing priorities and the progress of knowledge and technology to show how the industry got to where it is today. This broad overview is shown against the backdrop of three epochs in which different developmental priorities prevailed. In the first and longest epoch, the possibility of human flight was contemplated and challenged. It was followed by the race to get human flight to work in every aspect of the endeavour and to get it useful and practical. In this second epoch began the economic growth by which aviation became established as an integral part of the transport industry. The third and current epoch has priority on flight efficiency to prolong sustainability of this still fast-growing industry.

The focus of this review was on the emergence of the current dominant configuration, with the single central main wing, typically employing a flap, and the slender, tubular fuselage with an empennage. The next chapter discusses work on selected alternatives, potential rivals to the dominant configuration.

Of the thousands of people, events and projects which played an instrumental role in getting this enormous industry established, only the key contributors of relevance to this discussion are mentioned. Figure 2.1 illustrates their time in history and when their important contributions became recognised. The figure also indicates the convergence of these influences on the dominant configuration, which has remained unchanged since 1958.

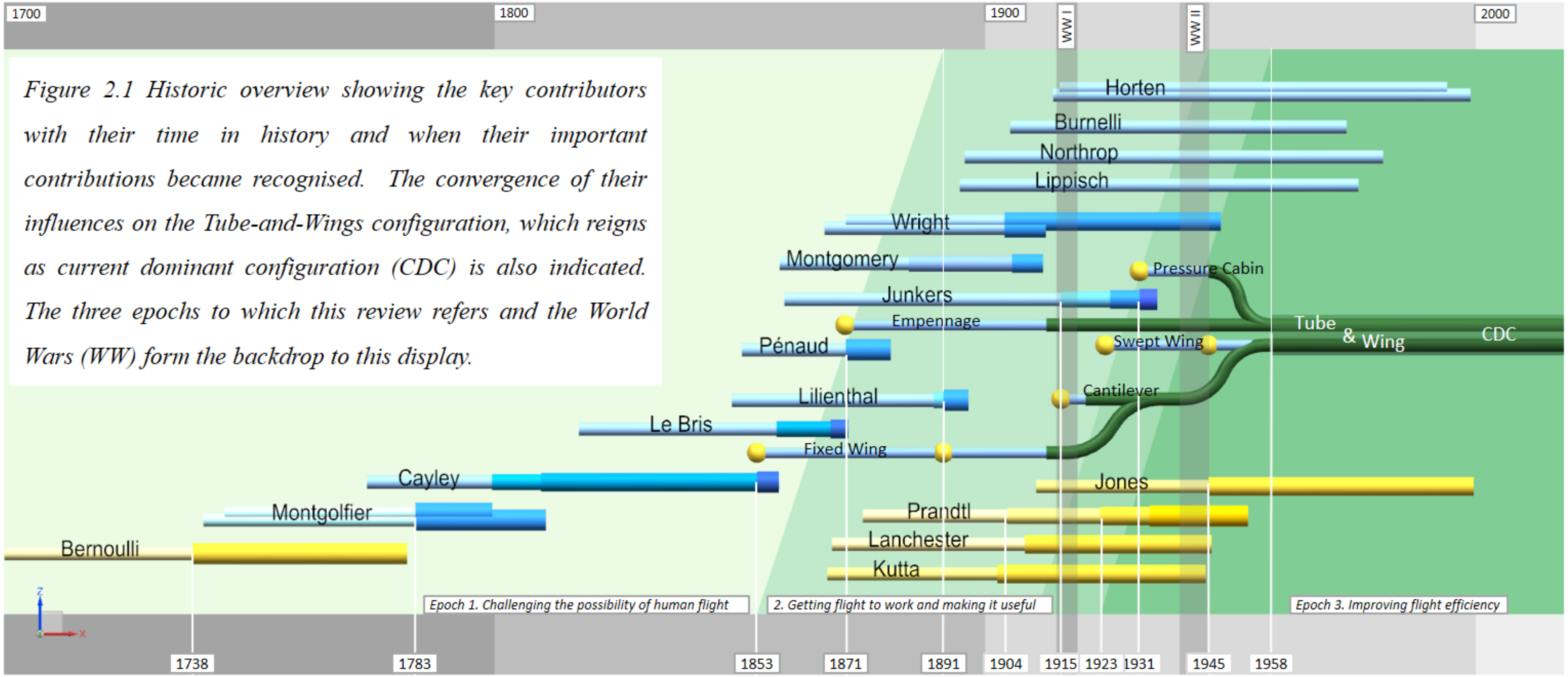

Figure 2.1 Historic overview showing the key contributors with their time in history and when their important contributions became recognised. The convergence of their influences on the Tube-and-Wings configuration, which reigns as current dominant configuration (CDC) is also indicated. The three epochs to which this review refers and the World Wars (WW) form the backdrop to this display.

2.2 Epoch 1: Challenging the Possibility of Human Flight

The first epoch saw humankind contemplate, challenge and ultimately demonstrate the possibility of human flight. This, the longest epoch, conclusively ended with repeatable demonstrations of human flight in 1891 by Otto Lilienthal.

2.2.1 Early Demonstrations of Flight

While every new endeavour first requires demonstration of its possibility, for most of its existence, humankind was without the demonstration of human flight. However, the possibility of flight itself has always been readily observable by the natural examples of birds, bats, insects and seeds. Flight must have captivated the imagination of many, yet the early attempts by those who dared and dedicated their energy must have been viewed, perhaps by most, as ludicrous and lacked the spirit of support. The idea of human flight first became credible in 1783 when the Montgolfier brothers showed that man *can* travel in the atmosphere. But the conquest of wing-based flight remained unresolved for another century [1]. Its pioneers had little else to guide them but the natural examples.

2.2.2 First Attempts at Wing-Based Flight

Guided by such working examples, many early attempts resembled natural flyers. The 'artificial birds' by the French sea captain Le Bris in 1857 and 1868 could serve as prominent examples. His designs showed testimony of observations, during his ocean explorations, of the flight of the albatross, which only very few at the time had the privilege to observe. Yet, significant success eluded him [1].

Four years earlier, Sir Cayley achieved the first well-noted gliding flight in 1853, in which a man was carried in a heavier-than-air machine, though without control. At the age of 79, a lifelong commitment to pioneering work in aviation culminated in this single flight. However, his studies lay the first scientific foundations as early as 1799 when he introduced the four basic forces of flight [2]. He proposed the easier road of the fixed-wing aircraft with separate propulsion, while many were struggling on the complex path of flapping-wing aircraft, attempting to use the wing for both lift and thrust. For these contributions with three landmark publications in 1809, 1810 and 1852, Sir Cayley is recognised as the father of aerial navigation [2, 3]. At a time when attempts at flight were not seen as useful or serious research, given that the Industrial Revolution set more important demands, the exploration was otherwise left mainly to amateurs who contributed little to the dissemination of the understanding of flight.

In the context of this work, it is relevant to point out that Cayley introduced the idea of separating the challenge of flight into the four departments of lift, balance and control, payload container and propulsion. These are the departments by which any aircraft configuration is defined. It should also be noted, that some of his illustrations even showed the essential features of the configuration, which is at the base of the current dominant configuration.

2.2.3 End of Epoch 1

His studies of bird flight also got Montgomery trapped in the intricacies of flapping-wing flight before his fixed-wing flight in 1884 became a historic success, though drawing very little attention [1]. In contrast, the studies of bird flight by Lilienthal, published in 'Der Vogelflug als Grundlage der Fliegekunst' (bird flight as the basis of aviation) [4] five years later in 1889, received immediate attention and became rather influential. When only two years later, he surprised the world with his repeated gliding demonstrations, all remaining doubt about the possibility of human flight was finally removed, thereby bringing the long first epoch to an end in 1891. Helped along by the worldwide distribution of action photos, the world was changed forever, knowing that man *can* fly. In his attempts at powered flight, Lilienthal also ventured onto the path of the ornithopter, distracting him from further significant progress in his remaining five years [5].

2.3 Epoch 2: Getting Flight to Work and Making it Useful

The second epoch got the aircraft to work with its wings, controls and power plants. In parallel, the basic understanding of the physics of flight became established. The later period of this epoch was dedicated to making the aircraft useful, reproducing working solutions and beginning to grow economic activities.

No longer doubting the possibility of human flight, the next priority was to find a feasible approach to aircraft development, to find solutions to the challenges of control and propulsion and to find the best arrangement of all the essential elements, all the while remaining safe.

2.3.1 Early Approach to Aircraft Development

Among the few who pioneered the emerging industry, the approach to aircraft development was divided. Some (like Lilienthal, Pilcher, Chanute and the Wright brothers) held that human flight would best evolve from gliding experience. Others (like Ader, Maxim and Langley) gave priority to the challenge of powered flight because flight without a propulsion system would offer no practical significance. Those who chose the gliding-first approach could focus their attention on the challenges of lift and control, while the others had to resolve simultaneously the formidable challenge of thrust from an onboard energy system of sufficient power density. Gliding has since Cayley, Montgomery and Lilienthal continued to play an important role in testing ideas in aviation. In this work, the gliding-first approach was also followed and was recommended for the next big steps to develop the ideas presented here.

2.3.2 Wing-Based Controls on Rigid Airframes

After the challenge of lift had been resolved, the success of flight was inevitably linked to the success of control. Those following the gliding approach could immediately experiment and refine the methods of control and gain valuable flying experience. Lilienthal's hang-gliders involved static margin control by means of weight shift for both pitch and roll control. He was also working on a glider with variable wing sweep, presumably for pitch control [5]. On the day of his fatal crash in 1896, he was trying, for the first time, a form of elevator control using a strap tied from his forehead to the tail surface. Although he thus never used the other means of control, static margin control was soon abandoned for use in active control until the modern version of the hang-glider emerged. However, weight-shift control does feature in modern aircraft for trim control of pitch, when, for example, fuel is relocated during flight.

The important ability to control roll by twisting the wing was taken by Wilbur Wright from his observations of bird flight and was, at the time, a major accomplishment in the attempts of getting flight to work [3]. So was the implementation of the rudder to combat adverse yaw [6]. Wing twisting was replaced by the simpler means of using wing-based control surfaces and the elevator, rudder and aileron gradually became dominant devices for control. The example of the bird, both in terms of wing twisting and pitch control using static margin control, was soon abandoned. As is typical of engineered structures, airframes were also made essentially as rigid structures from early on. In the context of this work, the issue of static margin control versus that of elevator control played a central role. Its early abandon and the change to the easier wing-based controls on otherwise rigid airframes had an important consequence for aviation development.

2.3.3 Agreeing on Aircraft Stability

While aircraft control concerns maintaining or changing the balance of flight, the partner challenge concerns stability. Since balance can be stable, neutral or unstable, a choice was required and consensus on this choice was expected. Bryan published work on stability in 1904 and suggested that failure to understand stability might have been the cause of many fatal accidents [7]. Inherent or passive stability was widely regarded as the safer approach to balance, but the Wright brothers preferred the responsiveness of unstable flight [3]. This required continuous pilot attention, quite acceptable for the short demonstration flights of the time, but not desirable when trying to apply flight to useful roles. Their success, which was largely due to having full control, prolonged the debate about unstable flight until about 1910. Till then, many aircraft must have had their centre of gravity behind the neutral point, which allowed a horizontal tail wing to serve as a second lifting surface.

Free-flight, by definition a form of flight without active controls, requires passive stability on all three axes to show repeatability. Pénaud of France demonstrated such stable flight in Paris already in 1871 employing a rubber-powered free-flight model with an adjustable tail assembly [1, 3]. His model must have had the centre of gravity ahead of its neutral point. When the inherently stable arrangement became the preference, the centre of gravity was moved ahead of the neutral point and this would typically require a downforce from a tail wing during much of the flight. This rather minor modification brought the arrangement in line with that of Pénaud, who is therefore generally credited for the introduction of static stability [1, 8] by means of an empennage.

Today, static stability remains enshrined in most aviation regulations and thus being an unnegotiable design requirement. Therefore, the empennage, the vertical and the horizontal tail wings on a rather long mass-balanced tail boom, have perhaps become the main defining features of the current dominant configuration, also referred to as the Pénaud arrangement or the tube-and-wings configuration. As separate wings for the purposes of stability, control, damping and trim, the empennage separated these functions from those of the main wing in the multi-wing arrangement. This elegant isolation is credited for offering a simple and robust solution to the critical challenge of stable balance, but perhaps not without compromise on flight efficiency. Therefore, its consideration played the central role in this work.

2.3.4 Arriving at the Dominant Wing Arrangement

Success of flight did not come with flapping wings, but came when the fixed-wing idea was put to the test by gliding flight. However, for more than two decades after Lilienthal, how best to arrange rigid wings remained an open question. A reliable answer to this question slowly emerged with the growing understanding of lift and drag.

Concurrent with the early experimental efforts ran the quest for understanding the physics of flight and the ambition to formulate this into predictive theory, mathematically described. It seemed that early experimental and theoretical work often took place entirely disconnected from each other. Some were practically inclined and found their way by trial and error. At the other extreme worked theoreticians, drafting complex mathematical models to express aerodynamic phenomena associated with lift and drag [7].

When Kutta and Zhukovsky (Joukovski) independently developed useful mathematical models based on the recognition of wing circulation, published in 1902 and 1906 respectively, a solid foundation was cast for the understanding and the mathematical estimation of lift.

Significantly smaller than lift are the forces of drag, but these are decisive in terms of the economy of flight and therefore remain a priority of aeronautic research. Understanding of their causes began to consolidate at the same time. Contributions by Prandtl in 1904 [9] with descriptions of the viscous boundary layer and flow separation were critical. With early aerofoils predominantly of the single-surface style, the structural superiority of a braced vertical stack of wings was exploited. The implication on drag from the external braces and the stacking of wings was hard to quantify. When it was realised that, without much penalty on aerofoil drag, the wing could offer useful volume in which much or even all of its structure could reside, the single-surface aerofoil began to disappear from common use. Junkers introduced the cantilever wing on the J 1 in 1915 after filing his wing volume patent in 1910 [10]. This patent represented an important landmark in the debate on the usefulness of wing volume, an ongoing debate that is central to the current work, as detailed in Chapter 4. With the J 13, the cantilever wing began the first passenger service in 1920.

The force of inviscid drag remained a mystery until deeper into the second epoch. Perhaps most important was the recognition of the vortex systems of the bound, the trailing and the starting vortices induced by a finite wing. When Prandtl and associates developed the lifting line theory in line with ideas which Lanchester had published in 1907 [11], a practical tool emerged, mathematically expressed and empirically validated, to calculate lift and induced drag on a finite wing. In 1923, Munk and Prandtl provided a clear guideline for the best circulation distribution along the span of a wing and the tools to prescribe the planform and the twist for achieving this [12]. Since then, the classical theoretical result has shown, that the elliptical spanwise circulation distribution would shed minimum kinetic energy into the downwash induced by the wing to offer the best span efficiency of $e = 1$. In other landmark publications at the same time [13, 14], they explained the consequences of stacked and staggered wings. From then on, the monoplane was justifiably preferred as the primary lifting device and the cantilever wing containing the structure and the fuel became a dominant configurational feature.

Insight into downwash for lift and its induced drag made clear the importance of the large effective span. The influence of structural wing mass on induced drag gave cause to reconsider the ideal circulation distribution under various assumptions about the structural design of the wing. In a publication in 1933 Prandtl [15, 16] proposed a revised circulation distribution, theoretically ideal for another set of assumptions about the structural mass of a wing. Since then, the issue of ideal circulation has remained one of the debated fundamentals of aeronautics, prolonging uncertainty and stimulating consideration of alternative configurations [6, 17-19].

The Junkers volume patent gave priority to the idea that the entire aircraft should ultimately consist of only a wing. Payload and engines should all be contained within a wing of sufficient volume. At the time, this idea seemed reasonable in the light of the growth in size of aircraft while these were still comparatively slow and therefore required enormous wings. His G38 had space for cargo and walkways in the wing. When Junkers, in 1924, introduced the wing flap in the form of a small secondary wing element, the achievable maximum lift coefficient was increased so drastically that the size of the wing could almost be halved. It then became apparent that wing volume would not be sufficient for the payload if the logical trend towards the smallest wing were to be pursued. Moreover, the introduction of the flap with its typical strong nose-down pitching moment emphasised the need for a balancing tail wing. Junkers, who was very instrumental in making aircraft useful in the budding airline industry, abandoned the pursuit towards the all-wing aircraft after the huge G38. Furthermore, his canard design, the J-1000 of 1930, which would have had the passengers within the wing was never built. Instead, he again committed his attention to the tailed aircraft, of which the very successful Ju 52 is a well-known example. Entering service in 1930, this was already a representative of the current dominant configuration, the tube-and-wings configuration.

2.3.5 Adopting the Pressurised Cabin

In an endeavour to make flight more useful, practical and economic, the benefits of flying above bad weather at lower air density and temperatures had to be exploited. Airliners briefly tested the use of oxygen masks before cabin pressurisation became the norm [20]. Again, Junkers was at the forefront of this development when the Ju 49 was used to investigate high-altitude flight with a pressurised cabin in 1931. However, the concept only entered into airline service in 1943 with the Lockheed Constellation and became widely used only after World War II. From then on, the fuselage cross-section was typically round, the ideal shape for pressure vessels in terms of the wall stresses. This presented an important structural implication for the layout of the fuselage.

2.3.6 Evolving Propulsion Systems

The development of practical aircraft was always constrained by the technology of aircraft engines. The successful gliding-first approach to the development of the aircraft implied that the first aircraft were powered by a component of weight, leveraging forward motion from loss of height. In this approach, the additional complexity of an on-board thrusting system for gaining or maintaining height was historically a subsequent developmental step. In most historic cases, the onboard energy system can be considered as an addition to the basic arrangement with little influence on the original arrangement and with the aircraft remaining capable of gliding flight if the thrusting system failed. Therefore, the development of power plants could progress in parallel towards improved power densities and efficiencies. This progress is ongoing, most crucial to the economy of the industry. Still today, airframe and engine development remain on separate tracks.

Due to the low power density, efficiency and reliability, aircraft of the early part of the second epoch were of low wing loading, slow, with short range or endurance and showing a notorious safety record. For flight to become more reliable, advances in engine technology were essential. Perhaps the most significant step-change came with the introduction of the gas turbine towards the end of World War II. Not only did it remove the flight speed barrier of propeller tip speed limits to expand the flight envelope beyond the speed of sound, but the service ceiling was also significantly raised. Today, the bulk of the revenue services operate close to the sonic drag rise at altitudes far beyond the occupant tolerance limits of temperature and pressure, which makes the climate-controlled pressurised cabin such an essential feature in the industry.

Until now, the dominant aircraft thrusters in the domain under consideration remain the propeller, the jet and the ducted fan. Furthermore, the thrusting units are typically separate fuel-burning systems, which could be placed on any airframe in a variety of arrangements. Looking at any aircraft arrangement of wings, controls and payload container, a variety of superimposed thruster arrangements can be found, suggesting that the basic arrangement takes precedence over that of the thrusting system. Ideas of integrating the propulsion system differently into the airframe have not yet changed the industry in terms of the current dominant configuration, Such developments are mentioned in the next chapter where alternatives are considered. It should be noted, that the basic dominant configuration is the same for powered and unpowered aircraft.

2.3.7 Adopting the Swept Wing

With the emergence of the turbine engine, higher cruise Mach numbers came into reach. In 1945, the work of Jones of NACA [21] reminded the aviation industry of earlier observations by Munk (1924) [22], Busemann (1935) and Betz, namely that the critical Mach number and hence the operational cruise speed could be increased by sweeping the wings. Before the turbine made the higher flight speed possible, this observation may have been of little interest. Now, several designs were reviewed to implement this concept, perhaps most notably the B-47 Stratojet of Boeing. This was also the first aircraft to fly the podded turbine on a pylon under the wing when it entered service in 1951. As such, this aircraft can be seen as the first to show all the features of the current dominant configuration still applied to the airliner today. The Boeing 707 of 1958 then came with the low-wing and modern undercarriage arrangement and the configuration of the airliner of today was born. Designers explored variations of engine placement and empennage arrangement, but eventually remained with the same arrangement as that of the 707. By this time, the sailplane also had all the features of its modern descendants. Therefore, all the building blocks of the basic aircraft arrangement had found reliable solutions, had been made to work and had evolved for practical use in the growing transport industry. The second epoch was over, having established one configuration that would dominate in human aviation, whether applied to a sailplane or an airliner or any other typical flight objective.

2.4 Epoch 3: Priority on Flight Efficiency

The current epoch has priority on flight efficiency and lately also on noise reduction. On the one hand, this drives the continuous refinement of every element of the transport system. On the other hand, it stimulates the search for better alternatives for the basic aircraft arrangement.

While flight efficiency always was on the mind of aircraft designers, it may have had lower priority while more basic challenges still needed attention in the race against competitors or enemies. Furthermore, a commitment to refinement must be preceded by good configurational choices and by the establishment of working solutions. Meaningful progress in terms of efficiency also required maturity of the basic theories of flight and therefore, the third epoch began when the tools for predicting induced drag were available as shown in Fig. 2.1.

2.4.1 Predicting Aerofoil Properties

The focus of this work was not on the refinement of the elements but rather on the investigation of the basic aircraft arrangement. However, one element continuously being refined, the aerofoil, is discussed due to its important influence on flight efficiency. The prediction of aerofoil properties was perhaps the most problematic issue which had not been resolved during the previous epoch. This remained largely an empirical art until computational codes began to produce reliable predictions very much later. Thus, for more than half a century, the art of aerofoil design included elements of educated guesswork [23]. It also required tremendous efforts of systematic observation and cataloguing. Macroscopic aircraft parameters could reliably be prescribed by the designers, but the influence of the details of geometry on drag relied largely on estimations and still involves a respectable margin of uncertainty today. Committing an inferior aerofoil (or other geometric details) to a design would penalise the economy of all aircraft in operation throughout their operational life. Earlier design deficiencies become visible only against subsequent improvements. Improvements of the design tools become visible in the convergence of their predictions and the observations.

On this topic, the sport of gliding played a major role by providing the opportunity for comparison of overall aircraft quality in the context of flight competition. A crucial advance came when the opportunity of laminar flow aerofoils was recognised and implementation on sailplane wings helped to mature their development. The tube-and-wings configuration seems particularly suited for the adoption of such aerofoils as the main wing can be specialised for its lifting function with any kind of aerofoil character. Some other arrangements require special aerofoil characteristics that may not necessarily be conducive in terms of laminar flow. Aerofoil refinement remains a primary focus of sailplane development today [24] and is perhaps a key reason for the dominant configuration remaining superior in the scene of gliding.

While aerofoil development can be considered a generic matter when considering aircraft configurations, there are some configurations where flying qualities are more sensitive to aerofoil properties than others [25]. Some older laminar aerofoils proved quite sensitive to in-flight contamination by insects or rain. While the tube-and-wings configuration seemed quite tolerant to bad-natured aerofoils, certain alternative configurations acquired bad reputations due to these unwelcome sensitivities [25]. Modern initiatives focused on aerofoil drag reduction include active systems of boundary layer control as part of the propulsion system. For these interactions, aerofoil development and integrated propulsion become configurational issues.

2.4.2 Converging on Speed of Flight and Finding Limits of Aircraft Size

In the airline industry, the progress towards ‘faster, bigger, further’ finally seems to have converged with specific niches of range and size gaining prominence, while others did not align with expectations. In terms of speed, the utility value of flight is inevitably linked to the time of travel and this, in turn, is directly related to the propulsion technology. When turbine propulsion entered service, it was immediately evident that the economic trade-off between the value of time and the cost of flight speed [26, 27] would find its balance where the drag rise of transonic speed occurs with wings suitably swept. The viability of supersonic travel had its test in history with the Concorde in service between 1975 and 2003. Only 14 aircraft were in service over these 27 years and unique troubles of route restrictions eroded the economic viability. Currently, several developments are under way, with a new focus on supersonic business flight. It might be fair to assume that the aviation sector of commercial supersonic flight will never be without development activity, but it is unlikely that this sector will ever become the economically dominant sector of the industry. Similarly, ballistic flight beyond the atmosphere might always receive attention, but will probably never become more common than subsonic atmospheric flight based on dynamic lift. On the contrary, a slight reduction in the cruising speed might be expected so that the need to sweep the wings could disappear again. The little time then added to the comfortable segment of the journey could quite easily be regained by making other portions of the door-to-door trip less time-consuming. This is particularly important to consider for the most popular routes, which have a relatively short cruise segment. Furthermore, cargo is not all that sensitive to travel time and the little time saved hardly justifies the adverse consequences of cruising at the edge of the transonic envelope.

In terms of size, the industry very early introduced the capacity of the Boeing 747 and since then aspired to go even bigger. This aspiration came from the anticipated elaboration of the hub-and-spoke network of routes with airport congestion presenting a major driver towards larger aircraft. It was suspected that the square-cube law would impose some limit on the size of aircraft of the tube-and-wings configuration [28] or that airport infrastructure would not be able to handle conventional aircraft of larger size. This has spurred many studies of very large aircraft of alternative configurations. When the Airbus A380 entered service in 2005, it demonstrated that the conventional configuration could be applied to carry more than 800 passengers and that upgraded airports could handle conventional aircraft of this size. However, it also showed that such a capacity is not as popular as was anticipated. With the point-to-point route network gaining popularity, over the hub-and-spoke network, it is questionable if larger aircraft will ever be reconsidered. The early termination of production of the A380 at the time of writing is perhaps the strongest signal that the economical limit of size had been exceeded. Best revenue is earned by aircraft of smaller size such as the Boeing 737 and the A320 [29]. Similarly, in terms of distance, most revenue comes from the shorter routes rather than from the extreme long-haul.

2.5 Summary and Concluding Remarks

The tube-and-wings arrangement remains firmly entrenched as a single configuration able to serve the entire scope of useful size and speed, forming a robust and reliable basis for the aviation industry to continue refinement of all the details. With the single central fuselage of the transport plane essentially a slender pressure vessel and its unbraced wing essentially a fuel tank, this configuration reflects good use of its shape to meet the complex array of requirements. First coming into the historic records through Cayley in 1804, then demonstrated as a free-flight model by Pénaud in 1871, for a while the dominant arrangement shared the stage with many other ideas. Prandtl and Munk consolidated a useful theoretical foundation about lift, drag and wing arrangement to support these configurational decisions. Junkers implemented the monoplane cantilever wing in 1915, added the flap in 1924 and pressurised the cabin in 1931. By then, all the defining features of the tube-and-wings configuration were established. Jones stretched the limit of the speed envelope of transonic flight by reviving the implication of swept wings in 1945. After the war, new requirements for bombers led to the development of the V-bombers in Britain and the B-47 Stratojet in the USA. This was the last full-scale experimental comparison during which several different configurations were considered and put to the test. From this the B-47 emerged as a precursor to the Boeing 707 through which the current configuration began its dominant reign, bringing the second epoch to a close in 1958, at least so it would seem.

Then began the long road of refinement of the transport jet, which has since served the industry well, based on the unchanged configuration. The industry focused on improving all the details of the robust solution, never again changing the basic layout. Understanding, tools and technology continued to improve, enabling substantial refinements. Interestingly, also the sailplane of today had the benefit of 60 years of refinement of the same configuration, culminating into the fastest, most far-reaching solar-powered personal transportation system yet achieved. Will further refinements allow convergence onto the ultimate physical limit of flight efficiency or can the bar be raised by a significant increment by stepping over to another configuration?

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Chapter 3

Alternative Aircraft Configurations

3.1 Motivations to Explore Alternatives

The search for best solutions for more than half a century during Epoch 2 inevitably required the exploration of the diversity of alternatives. If the convergence on a single preferred arrangement came as expected, it might not be obvious, why alternatives remained of interest thereafter. Because there will always be diversity in the set of design requirements, textbooks on aircraft design give due prominence to the first step of selecting the most appropriate configuration before committing to the details of design. The configuration ideal for one specific design may not be ideal for another. However, when focused on the typical flight objectives, like those at the core of revenue services in this industry, it is important to ask: Why are alternatives still considered even in this well-established field? The fact that this is done with sincerity is evidence that not all are convinced of the superiority of the current dominant arrangement. In that sense, the second epoch is not over yet and one may ask if it could ever be. The uncertainty about which arrangement is best may prevail.

At the time when the industry accepted the most important choice with such finality, the state of knowledge and technology was less mature, some ideas had not been tried and many design tools were not ready yet. 'Best' solutions were perhaps best for a set of criteria with lower priority on flight efficiency, when it was more urgent to begin operations than to optimise. Whatever the reasons may be, there seem to be many who hold the opinion that an aircraft arrangement of better efficiency might look different to the one in dominant use today [1].

In the spirit of remaining critical of the fundamental assumptions and earlier conclusions, even the classical explanations of fluid mechanics of subsonic flight are being challenged [2]. The biplane and the stagger wing theorem and the ideal spanwise lift distribution proposed a century ago by Munk and Prandtl are being questioned. Similarly, doubt prevails about the empennage. Is it part of the best solution? Could the downward tail load be avoided? Should the fuselage contribute to lift? Should the payload reside within the wing? Should the span be increased? Is there a limit on size beyond which another configuration becomes superior? Perhaps new materials or technologies of control allow arrangements that were previously not feasible. Perhaps new design and optimisation tools will find different arrangements as ideal when the complex interactions of competing requirements are more rigorously balanced. Perhaps the integration of propulsion systems into the airframe requires a different arrangement to be best.

3.2 Scope of Discussion

Such questions keep the exploration of alternatives ongoing and in the following paragraphs, the most prominent initiatives concerning the typical flight objectives are briefly mentioned in their historical context. In Chapter 4, the aircraft design space is shown in an imagined family tree to propose conceptual relationships for comparison of flight efficiency among these configurations. Both airliners and sailplanes are designed around the typical flight objective of which the priority is to cover distance with best flight efficiency. Therefore, this discussion is limited to such applications. While the emergence of unmanned aerial vehicles offers a young field for exploration of alternatives, their flight objectives are often non-typical when special requirements concerning take-off and landing call for special arrangements. Similarly, the emerging field of VTOL aerial taxis, with its current rich diversity of configurations, is not considered to reflect the typical flight objective within the domain under consideration due to propulsive lift being excluded from this domain. Therefore, alternatives for special flight objectives, while not overlooked, are not discussed in this chapter. From the enormous scope of alternatives, only a few are mentioned for their relevance to the further discussion.

3.3 Canard Configurations

The early choice of the Pénaud arrangement was driven by the requirement for passive stability. Now that fly-by-wire systems have come to maturity, passive stability is no longer technically compulsory. However, for unaugmented piloting, preference or even regulated requirements for stable flight prevail. Early experiments showed that longitudinal stability and control were easier to provide with some arrangement of multi-wings. Of these, the tandem wing represents the variant of staggered wings of approximately the same size, while the Pénaud and canard arrangements have a larger main wing either forward or aft. While the stagger theorem of Munk suggests that wings could theoretically be staggered in any way, other considerations lead to the small tail wing arrangement being preferred. With a stable static margin, the horizontal tail wing may then be required to produce a down-force during cruise. A good trade-off between tail boom length and tail wing size (and down-force) is such that the typical fuselage is comparatively long to allow for smaller tail wings. The rearward extension inevitably calls for mass balance in the front and therefore, the fuselage is typically also stretched forward. A defining characteristic of this dominant arrangement is thus the fuselage of high fineness ratio (length over diameter).

A remedy to these penalties of the Pénaud arrangement may appear to be its counterpart with the smaller balancing wing in front. With the canard also lifting during cruise, it does not have to be small nor separated far from the centre of gravity and the main wing can be smaller. Furthermore, mass balance of the canard and the joining boom requires no fuselage elongation.

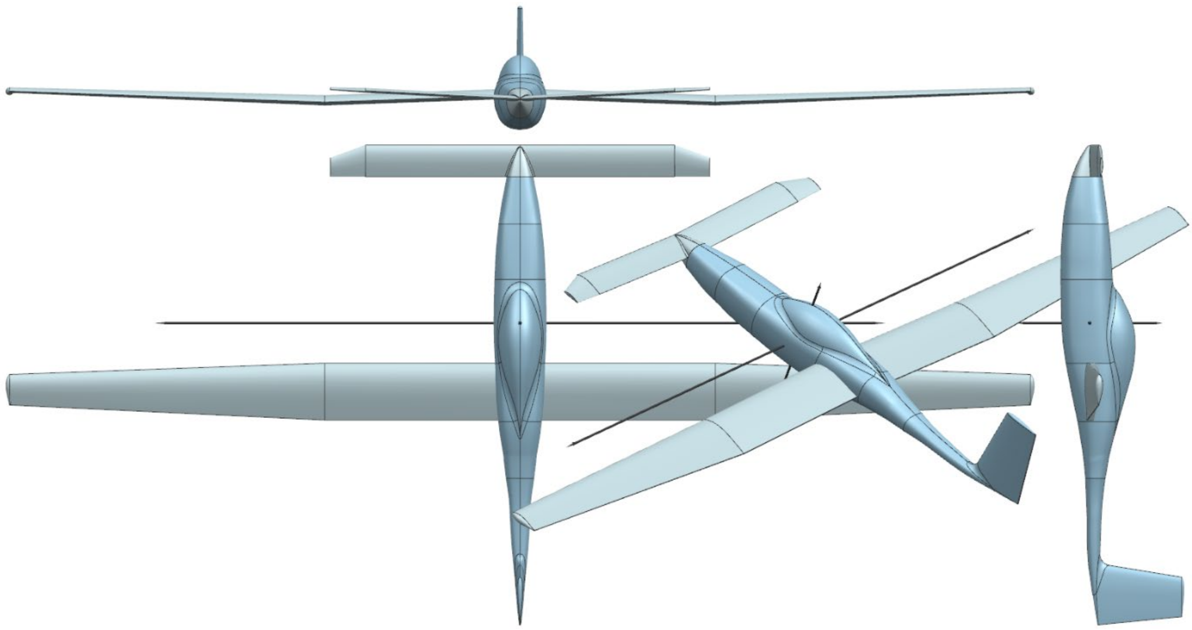

Figure 3.1 Solitaire canard sailplane by Rutan with the centre of gravity shown between the lifting surfaces.

The canard has been featured in many designs since that of the Wright brothers and it has been a signatory feature in designs by Rutan. Perhaps a final performance evaluation of this arrangement came with Rutan's Solitaire sailplane in 1982 [3]. In gliding competitions, which serve as the arena for comparison of all-round flying qualities, the canard sailplane had a chance to demonstrate superiority over the Pénaud arrangement. Having failed to do so, the canard configuration never became a serious rival to the dominant Pénaud configuration. However, it should be noted that the Solitaire had a conventional vertical tail wing with a rudder for yaw stability and control, thereby not taking advantage of losing the tail boom. Also, the design did not have the benefit of elaborate refinement. The trade-off among the multi-wing arrangements of the canard, tandem wing and tail wing was also numerically re-evaluated by McGeer et al. [4], who confirmed that the preference for the tail wing arrangement was technically justified.

3.4 Aircraft with the Tail Boom Reduced

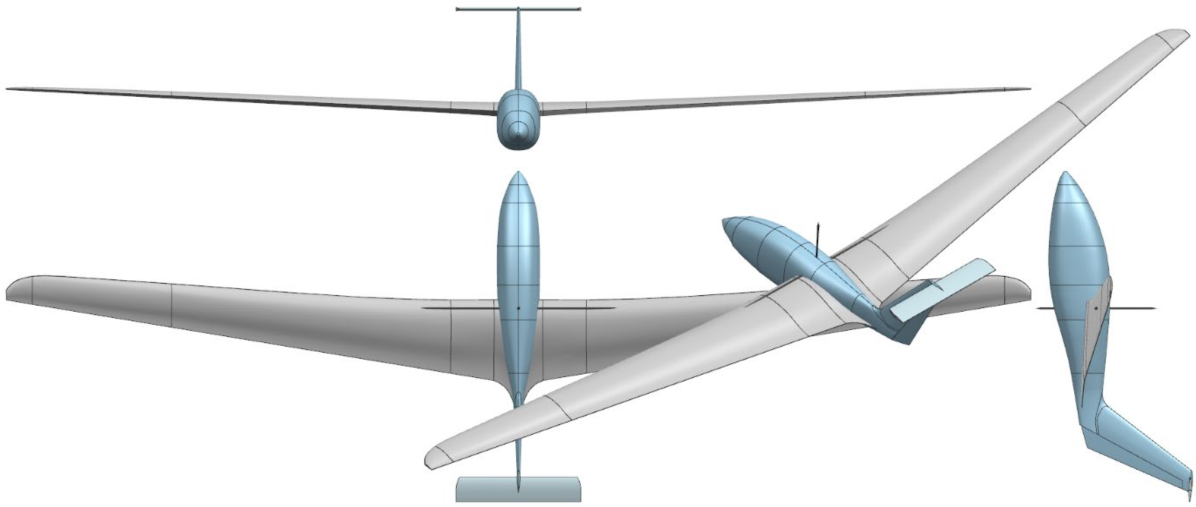

Figure 3.2 Genesis 2 glider by Marske with a small horizontal tail wing, the trimmer, on a swept back fin.

Remaining in the scene of sailplanes, Marske challenged the conventional dominant layout with a series of gliders beginning with the Pioneer series in 1967 and the Genesis series in 1992. In these gliders, the tail boom was significantly reduced to hold a vertical fin directly behind the main wing, with the fin swept back in the later versions of the designs. The Pioneer is without a horizontal tail wing, while the Genesis 2 has a small tailplane at the far tip of the fin referred to as a trimmer. Not taking advantage of the liberty of the mass balance of boom and empennage becoming relaxed, the pilot position relative to the wing root is here arranged as in conventional sailplanes, and therefore, the main wings are swept slightly forward to accommodate the forward location of the centre of gravity. Though much reduced in size when compared with a conventional sailplane, these fuselages still enclose much unused volume. The Genesis main wing aerofoils employ significant reflex, like in its predecessor, the Pioneer, which is essentially a tailless aircraft of the flying plank arrangement. Despite having a vertical fin and the trimmer, the Genesis is also normally referred to as tailless. The Genesis employs tip spoilers to improve yaw control effectiveness. Although this work culminated in designs of good handling qualities and performance and several kits and production models have entered the sport, this approach did not change the mainstream of sailplane design nor did it show much influence on aviation development in general.

3.5 Lifting Body Designs by Burnelli

Burnelli, who gained much aircraft design experience during World War I, tenaciously pursued the notion that all surfaces of an aircraft should contribute to lift. While Junkers proposed enlarging the wing for the payload, Burnelli proposed that a dedicated fuselage should remain but in the shape of a lift producing aerofoil. His aircraft designed between 1921 and 1946 all employed such lifting fuselages. They retained an empennage, functioning as in the Pénaud configuration, sometimes employing twin tail booms with vertical tail wings joined by the horizontal tail wing. At that time, cabin pressurisation was not yet in common use and cabin walls were thus not stressed by cabin pressure. Also, at that time, the art of aerofoil design was still without good predictability and much was left to experimental trials.

Much controversy surrounded the work by Burnelli so that it had little impact on the aeronautical thinking of the time. None of his designs became well known through visibility in widespread service or through his numerous patents [5] and this important idea of fuselage lift was received with little interest. Real interest emerged only some decades later when the lifting body idea was reconsidered in the blended wing body arrangement.

3.6 Single-Wing Aircraft

The designs of Burnelli, employing an empennage, belonged to the family of the multi-wings. Perhaps the most significant body of work on alternatives was also done in the family of the single-wing configurations. A few months before the Wright brothers, Jatho of Germany had flown a motorised tailless aircraft [6], its wings in the shape of a seed. Based on the same natural example were also the tailless gliders by Etrich beginning about 1906. The Charlotte of 1922 by the Akaflieg of Berlin and the Weltensegler of Wenk in 1923 might have followed the example of the Zanonia seed as well [6]. In 1910, Dunne began to design several tailless biplanes and monoplanes with a swept wing. At a time when lift still presented a major challenge, his aircraft did not provide for appropriate wing twist to prevent tip stalling, giving these designs a questionable safety reputation. At the time, the Pénaud arrangement was also not yet reliable and therefore, two rival ideas were racing for acceptance. Perhaps aviation history might have taken quite a different course if the tip-stalling problem of the tailless arrangement had been swiftly resolved. This was also the time when Junkers suggested, by his volume patent of 1910, that the aircraft of the future might be just a wing containing the payload and all within.

Perhaps the most prolific in the field of tailless aircraft were the Horten brothers, who championed the development of almost 20 different tailless aircraft designs between 1933 and 1960, first in Germany and after the war, in Argentina. The notion that the wing alone could serve as lifting device while offering balance and control, formed the basis of all their designs. Because they tried to avoid adding a separate fuselage, their designs are generally referred to as flying wings [6]. The war availed generous resources to the promise of superior reach for military missions by flying wings. However, their most memorable design would perhaps be the H IV sailplane of 1940, which was compared with sailplanes of the conventional configuration. Under special circumstances, when low wing-loading was beneficial, the performance compared very favourably with the best sailplane of the time, but it failed to demonstrate consistent superiority [6, 7] and ultimately had no influence on sailplane constructors, who remained true to the well-established tube-and-wings configuration. However, their

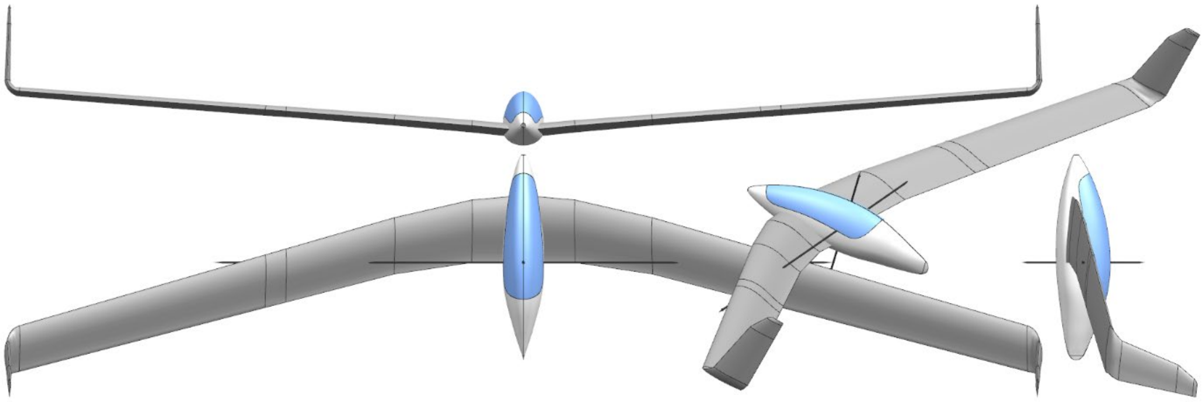

Figure 3.3 SB-13 Acrus of the Akaflieg Braunschweig with the centre of gravity made visible.

designs convincingly demonstrated that an empennage was not needed to obtain good handling qualities. Unfortunately, their designs offered good handling qualities at a high expense of efficiency. The flying wing arrangement seems quite sensitive to the trade-off between handling qualities and flight efficiency. With this topic at the core of this work, explanations are offered in Chapter 4.

Other important contributions came from Lippisch in Germany and Northrop [8] in the USA. Similarities between the Northrop YB-49 of 1947 and the earlier Horten H V and the H IX (Ho 229) are probably not coincidental, and therefore, as forerunners of the B2 Spirit bomber, their work can be seen to have culminated in the 21 flying wing bombers in service today.

The arguments in favour of the tailless configuration remained convincing and the observed shortcomings seemed in principle resolvable. This challenge was taken up by the Akademische Fliegergruppe of the University of Braunschweig (Brunswick) in 1982, when it began the development of a tailless sailplane for the standard 15 m class, the SB-13 Acrus [7]. The design team had access to modern design and manufacturing tools and could take advantage of the rich history of sailplane development. Troubled by difficulties with aeroelasticity and handling qualities [9, 10], the development was tedious and finally, the prototype was retired in 2000 to a museum without having made convincing demonstrations of superiority over its conventional rivals. Despite these difficulties, the Akaflieg Karlsruhe has recently (2015) embarked on a very similar project, the AK-X to gain from the lessons learnt from the SB-13. In the scene of F3B competitions, radio-controlled gliders of the tailless arrangement tried to outperform their rivals of the dominant configuration. Also in this scene, only limited enthusiasm remained for these tailless aircraft [7] when expectations were not met. Refinement of the conventional sailplane remains the focus of sailplane designers [11], who must offer winning improvements to their customers, every time a new model enters the market.

Far more successful in its field was the Swift ultralight, foot-launched sailplane, a design by Kroo et al. of Stanford University [12]. This glider began competing in the newly established category of Class II hang gliders some time after its first flight in 1989. Unlike the SB-13, the Swift did not have competitors which had the benefit of decades of refinement. The Flair 30 of 1990 by Rochelt of Germany [7] would have been a relevant rival, though of the same configuration. Unfortunately, its development was stifled by a fatal accident, which gave yet another blow to the reputation of the tailless configuration. The Archaeopteryx by Rupert of 2001 is a comparator of the conventional arrangement in the field of foot-launched gliders. These two designs seem to be the dominant competitors in the ultralight glider competitions with the Swift making a strong case for the tailless configuration. As these designs mature together, their comparison in competition will be a valuable indicator of all-round flying qualities. To date, the group of participants is still rather small.

Without many more examples flying today other than the B2 and the Swift, the tailless configuration may be seen as a suitable alternative only for special cases. The flex-wing hang-gliders and paragliders are perhaps good examples of such special cases where the tailless arrangement dominates in their fields. So far, the conventional tailless aircraft or the flying wing do not represent viable candidates to replace the current dominant configuration in the field of subsonic fixed-wing manned aviation. However, this view is again being challenged in a young initiative (2014) in which the flying wing is being reconsidered in the form of the flying-V. In this arrangement, the highly swept inner portions of the wings are sufficiently inflated to serve as the payload container. Research on this configuration provided estimates that an airliner of this arrangement could have about 20% better efficiency than its conventional rival [13].

3.7 Blended Wing Body Configurations

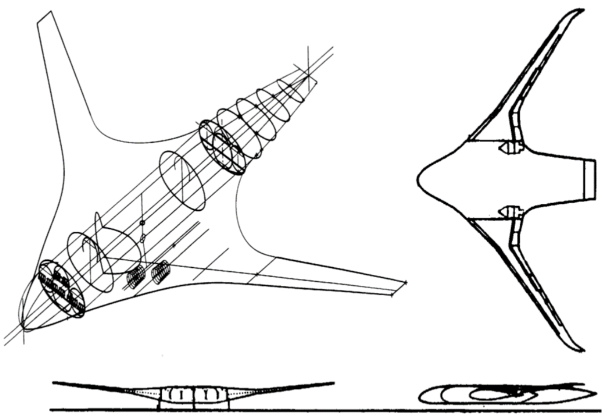

Figure 3.4 The first proposal by McDonnel-Douglas for a blended wing body arrangement [16].

Historically, the synthesis between the approaches of the lifting body and the flying wing started receiving serious consideration in 1989 when McDonnel-Douglas began work on the blended wing body (BWB) configuration [14]. Initial comparisons with the conventional MD-11 showed promising potential for improving flight efficiency and noise emissions. This first proposal, shown in Fig 3.4, should be kept in mind when looking at the work presented in this thesis, as it shows the features expected in the aircraft of the future as proposed in this thesis. Patented in 1990, it was not a radical departure from the conventional configuration by retaining the fuselage essentially as a stack of cylindrical pressure vessels arranged to give it a lower fineness ratio [15, 16]. A very significant comment by Liebeck [15] records, that: from this design, there was an ‘overwhelming tendency to converge back to the conventional configuration’. At that point, a decision was taken ‘to abandon the requirement for cylindrical pressure vessels. Removal of this constraint became pivotal for the development of the BWB'. The evolution then soon departed further from the conventional configuration by enlarging the sideways extent of the fuselage rather radically [17].

Initially, NASA backed this initiative at McDonnel-Douglas and later at Boeing (after Boeing acquired McDonnell-Douglas together with the BWB initiative). BWB development has been ongoing with varying intensity and has yielded numerous design studies [17]. In Russia, the Tupolev and TsAGI projects investigated at least five variants beginning in 1991. Though called flying wings [18], integrated wing body or lifting body designs, these are generally also mentioned in the literature under the heading of BWB research [14] as are hybrid wing-body type aircraft [19]. Also in Europe, the BWB idea received serious attention under the EU Framework Programmes 5, 6 and 7 between 2000 and 2012 under project names such as MOB [20, 21], VELA [22, 23], SAX 40 [24], NACRE [1] and ACFA [25].

Many variations have since been derived, some of which have flown at a smaller scale. The principal focus was on transport planes larger than the existing giants of the time. Concerned that the square-cube law of scaling would perhaps not allow the current dominant configuration to be scaled to very large aircraft and recognising that wing volume becomes useful at the larger size the consideration of such alternatives seemed justified. With the A380 now in service, the square-cube law concern was put to rest but more significantly, it became apparent that the drive towards larger aircraft is not in line with actual market demands. In this regard, it is problematic that BWB configuration seems less suitable for airliners of the smaller, more popular size, such as the A320 or the Boeing 737. Only very recently (2018) have studies been published concerning aircraft of this size [26] and it will be interesting to monitor the progress of such work.

The challenge of finding good compromises between competing requirements is overwhelming and the step to implement this new approach appears too large at this time. Structural challenges of cabin pressurisation [15] and operational concerns like emergency egress [27, 28] are often highlighted as major hurdles and consensus has not been reached on issues of basic shape and engine placement. It is not helpful that the BWB configuration is unsuitable for the sailplane or other small aircraft because it therefore has little chance of becoming established in less critical domains of aviation. However, the BWB investigations collectively present by far the largest efforts in history in the exploration of alternatives for the airline industry. The fact that such immense investigations are being made is a strong indication that the aeronautical community is confident that solutions superior to the current dominant configuration must exist and the BWB currently stands perhaps as the most popular contender. Reductions in fuel burn per seat are estimated by Liebeck [17] to be more than 25% while Yang et al. [26] mention expected improvements of up to 50%.

3.8 Strut-Braced Wings Reconsidered

Entirely in contrast to the approach of enlarging the wing for payload and structure is the concept of stretching the wing to a very high aspect ratio and making it very thin. Thin aerofoils are desired for lower profile drag and require less wing sweep for the same cruise Mach number. At lower sweep angles, better advantage may be taken from natural laminar flow aerofoils. However, such wings offer very little volume for the structure, fuel or ballast and certainly are not useful for the payload. The importance of span has been understood since induced drag had been recognised and the trade-off between structural mass and span has since been the topic of many optimisation studies.

Such slender wings stimulated a revisit of the external wing braces, reopening a debate that had been settled before. The modern versions would take advantage of advanced materials and the experience with laminar flow. Such concepts have received new attention towards the end of the previous millennium [29-33]. The challenge, in this case, concerns the details of the brace arrangement. In one conceptual approach, the braces are minimised in size to serve as structural supports alone. In another category of external bracing, the structure is formed by a pair of wings as in the joined-wing arrangements [34]. In total contrast to the prediction by Junkers, some of these wings will hardly have sufficient volume even for fuel. Such arrangements would serve as structural alternatives within the tube-and-wings configuration with estimated reductions of fuel consumption claimed to be as high as 47% [32].

3.9 Other Configurations Considered

There are many other configurations which had been tried and which are currently under investigation or reinvestigation. Much work is directed at alleviating noise pollution by shielding power plants, but all initiatives ultimately strive for better flight efficiency. The idea of the lifting fuselage is still alive beyond the BWB arrangement and receives attention by consideration of wider fuselage arrangements like the double-bubble layout [35]. Multi-body arrangements are being reconsidered and applied to special flight objectives such as spacecraft launching. Non-planar wing arrangements, new versions of tandem wings and different ways of bracing the wing in variants of the biplane can be found in box-wing or joined-wing arrangements. Many canard or three-surface aircraft are still flying but their numbers are insignificant when compared with the aircraft of the current dominant configuration.

3.10 Concluding Remark

Despite these ongoing challenges, it seems that the current dominant configuration remains firmly preferred as confirmed by the latest entries into the market in the airline industry and in the sport of gliding. None of the many proposed alternatives has yet been affirmed as a viable successor. However, the fact that alternatives are being investigated implies that in the opinion of many, superior solutions must exist and the results of these studies seem to support this opinion. Claims of achievable improvements of efficiency range between 20% and 50% [17, 32] which suggests that further pursuit might be worthwhile. However, the prominent competing proposals are contradictory in their strategy of providing useful volume. The blended wing body and the flying-V enlarge the central portion of the wing for the payload, while the strut-braced wing, the box-wing or the joined-wing reduce wing volume rendering it insufficient even for fuel and structure. This conflict concerning the usefulness of wing volume may explain the lack of consensus on the oldest question in aviation. It may be the reason for the hesitation on the most important design decisions in the first stages of aircraft design. Therefore, it may help to isolate this question from the complexity of application-specific full-mission aircraft design. The next chapter discusses how the wing volume can be related to the operational parameters of any aircraft within an isolated segment of the mission to shed light on the usefulness of wing volume.

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Chapter 4

Existence of a Family of Ideal Aircraft Configurations

4.1 Background

The previous two chapters discussed the landscape of aircraft development to show how and when the tube-and-wings configuration, as one of many possible, became dominant, being applied to the overwhelming majority of all aircraft designs. Nevertheless, interest in alternatives remains current, and one can divide the competing alternatives into two groups. In the one, volume for the payload is provided in the wing, leading to BWB-type configurations. In completely opposing developments, the aspect ratio of the wing is stretched so far that the volume of the wing is insufficient even to accommodate the entire structure within the wing, thus reintroducing external wing bracings in a variety of forms. These opposing approaches indicate that the topic of wing and aircraft volume remains an unresolved configurational issue. Therefore, this topic was investigated in the publication '*On the Wing Density and the Inflation Factor of Aircraft*' [1], which introduced a comparative reference and an associated metric as a foundation for this chapter. The publication appears in its stand-alone form as Appendix A.

4.2 Organising the Aircraft Design Space

Chapter 1 narrowed down the aircraft design space to the domain of fixed-wing, subsonic, heavier-than-air flight. Before mapping configurations within this domain, a few notions defined in [1] are summarised here.

4.2.1 Flight Objective, Ideal Wing and Inflation Factor

The design of any practical aircraft inevitably involves compromise to allow for a large variation in objectives and operational parameters. When looking for the ideal arrangement for a design, it is useful to have a reference that is not concerned with the trade-offs leading to such compromise. A reference without compromise must consider a unique objective and set of parameters from the large scope of variations. Here, the notion of the *flight objective* gives such focus. Then it is necessary to consider the physical limits of aerodynamics given a focused objective. Here, the notion of the *ideal wing* is introduced as a baseline for any given flight objective. Its volume can be unequally derived from the focused operational parameters. Against this reference, the aircraft volume of a corresponding real solution yields the *inflation factor*. This factor serves as a quantitative measure of discrepancy between a practical solution and its aerodynamically possible ideal. Thus, as a metric for relative aircraft size, different configurations can be compared with the common baseline of their ideal wing.

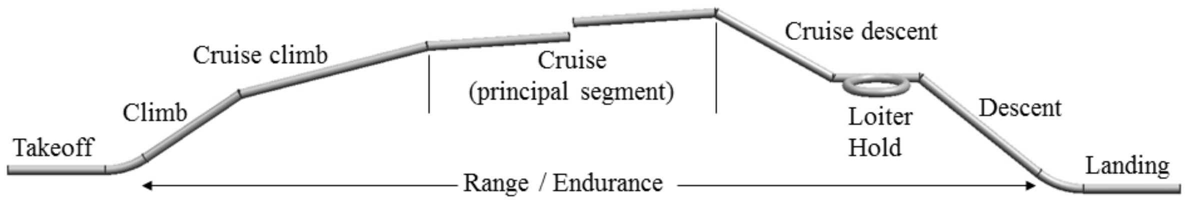

Figure 4.1 Any mission is a sequence of mission segments, each having a specific performance objective. Most of the time would typically be spent on the principal segment with little time spent on peripheral segments or emergency segments.

Flight Objective

Each aircraft is designed for a *family of missions*. Every flight represents one *specific mission* and Fig. 4.1 shows how such a mission is composed of a sequence of *mission segments*. Each segment has only one specific *performance objective* such as flying for maximum range or maximum endurance.

The family of missions sets the overall scope of *operational parameters* of aircraft mass m, the load factor n, air density ρ and the flight speed V. Figure 4.2 illustrates how each specific mission narrows down the scope of operational parameters while all the performance objectives of the family of missions may remain relevant. Each mission segment further narrows down the variation of operational parameters and now only one specific performance objective remains relevant. This performance objective, together with the operational parameters, define the *flight objective* of the segment. The flight objective is now unique.

The operational parameters come from the choice of speed and altitude and payload mass and the manoeuvre required for a mission segment. It is normally the objective to perform any mission with the best overall economy and this must therefore apply to each mission segment as well. Mission optimisation and operational constraints of the full mission will guide the choice of the operational parameters in each segment. However, for this discussion, it is unimportant how these parameters have been chosen.

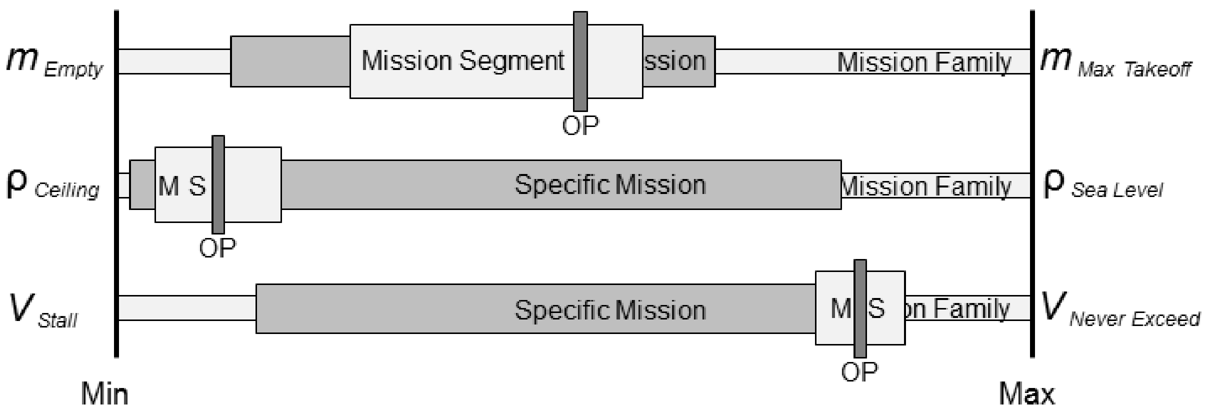

Figure 4.2 Operational Parameters (OP), namely all-up aircraft mass m, air density ρ and flight speed V, as narrowed down from the overall scope of variation of the Mission Family first by the Specific Mission and further by the Mission Segment (MS) to give focus to the operational parameters for a given flight objective.

The flight objective may then be defined as the objective to operate the aircraft at the operational parameters of choice (m, n, ρ and V) at the best flight efficiency for the given performance objective. An aircraft specialised for such a unique flight objective can be without compromise.

Ideal Wing and Inflation Factor

Assuming that the physics of lift-based flight requires a dynamic interaction between the flight body and its surrounding viscous medium to provide the lifting force for heavier-than-air flight, such a lifting device is assumed to be a wing (a fixed-wing, given the domain under consideration). By 1924, Prandtl and Munk [2-4] had already established how circulation would best be generated to minimise the inevitable loss to induced drag. From the variety of options of stacked and staggered wings of all arrangements, their theory makes a convincing case that the single straight wing with the ideal spanwise circulation distribution would give best efficiency when no other requirements call for compromise. Best span efficiency is thus a critical quality expected in any solution ideal in terms of flight efficiency.

Defined as a reference, the *ideal wing* would be the wing causing the lowest total drag physically possible to carry a given weight at the dynamic pressure of choice. With lift being the only consideration, such a wing does not present a practical solution for an aircraft but, it presents the limits of span and volume that are of interest as a baseline for comparison. The ideal wing should be viewed as a hypothetical aircraft with everything compressed into the smallest straight wing of high aspect ratio to have the lowest total drag possible. This geometry can then serve as a reference against which the quality of deviating solutions can be gauged. Each flight objective has an ideal wing of own size, which is a function of the operational parameters and the aerofoil and wing geometry parameters. As fully described in [1], the mathematical relationships have been developed to express the volume of an ideal wing Vol_{IW} as a function of its operational parameters, namely the aircraft weight mgn (with m the all-up mass and n the manoeuvring load factor), the airspeed V and the air density ρ. The ideal wing is taken to have an elliptical planform and is designed to operate at the design lift coefficient C_L and aspect ratio AR, which together will offer the lowest total drag. The aerofoil geometry is considered by the aerofoil area fraction f_{AF} and its relative thickness t. Wing geometry is considered by the planform transformation factor of the elliptical planform f_{PTE} as described in [1]. Then the volume of the ideal wing can be expressed as

$$Vol_{IW} = f_{PTE} f_{AF} t \sqrt{\left(\frac{2mgn}{\rho V^2}\right)^3 \frac{1}{C_L^3 AR}} \tag{4.1}$$

This is the smallest volume that an aircraft must have to fly a given weight at a selected dynamic pressure at the lowest possible total drag. Comparison with the actual aircraft volume Vol_{AC}, of a corresponding practical solution of the same all-up mass *m*, yields the *inflation factor IF*

$$IF = \frac{Vol_{AC}}{Vol_{IW}} \tag{4.2}$$

The inflation factor serves as a quantitative metric for relative aircraft size by which different configurations can be compared against the common baseline of their ideal wings.

4.2.2 Global Optimum and Ideal Configuration

Given a focused flight objective, it is in principle conceivable to provide an aircraft design that is specialised for this specific flight objective. This design can be without the compromise otherwise required from flight objectives of other segments of the mission. The best design for a given flight objective is defined as its *global optimum*. By definition, it is physically impossible to meet the given flight objective by any better design than that of the global optimum. It does not matter that such a design may be unknown or not achievable by the current state of technology. By this definition, a unique global optimum must exist for every flight objective.

The design solution of the global optimum must be based on one specific configuration. This is defined as the *ideal configuration* for that specific flight objective. Thus, by definition, each flight objective has only one ideal configuration. Again, regardless of the status of its identity, by definition, the ideal configuration exists and is uniquely and timelessly linked to its defining flight objective. There may be as many global optima (N_{GO}) as there are flight objectives ($N_{GO} \leq N_{FO}$), but the number of different ideal configurations (N_{IC}) will be relatively small ($N_{IC} <<< N_{GO}$) because many variations in the detail will be based on the same basic arrangement and thus belong to the same configuration.

4.2.3 Principal and Other Mission Segments

Every mission segment has its specific flight objective, global optimum and ideal configuration to which the arguments presented in this work can be applied. The real aircraft must at any time be able to adapt to *all* flight objectives of *all* the segments of *all* the missions that *all* identical aircraft should be able to perform throughout their entire service lives. Therefore, it is impossible for real aircraft to operate optimally throughout the full mission. Peripheral mission segments like take-off and climb or descend and landing or any emergency segment like flight with asymmetric engine failure must be flyable by the same design at any time. This means that either the same configuration must be suitable to all performance objectives or it must allow in-flight adaptations (like undercarriage extension) to form derived configurations suitable to other segments. By definition, the principal mission segment has the most important economic significance and therefore, the performance objective of this segment should have the most decisive influence on the choice of the basic configuration. This must be suitable to all other segments or form the basis for all derived configurations.

Therefore, this discussion focused on the group of flight objectives that have the same performance objective of the principal mission segments. For the majority of aircraft, this will be the objective to fly for maximum range. Depending on the propulsion type, this means, for example, that the aircraft will be designed for minimum drag when operated at the dynamic pressure of choice. Thus, the majority of flight objectives have the performance objective to fly with minimum drag at the dynamic pressure of choice.

Maximum endurance may be another prominent principal performance objective for which the ideal design would be operated at the speed requiring minimum power. Some peripheral mission segments would have precisely the same performance objectives as those of these principal segments. For example, the peripheral segments of climbing or descending may also have the performance objective to fly either with minimum drag or with minimum power. Therefore, the variety of economically important performance objectives is rather small. Furthermore, once all flight objectives are grouped according to common performance objectives, much diversity in ideal arrangements should not be expected.

By organising the entire aircraft design space in terms of flight objectives with common performance objectives, one must find many commonalities across the spectrum of all aircraft. One also finds clusters around certain dynamic pressures and aircraft densities. One such cluster, for example, captures the bulk of turbofan-based airline operations, where operational dynamic pressure for their principal mission segment of cruise does not show much variation. This cruise segment of the airliner and that of a sailplane both have the performance objective of maximum range. Their operational parameters differ in the magnitudes of the dynamic pressure and mean aircraft density but these differences may be reflected in the design solution only as a matter of scale and proportion. When comparing shapes or arrangements within the entire aircraft design space, it thus seems useful to consider isolated flight objectives, rather than comparing solutions compromised for all mission segments of the entire family of missions.

4.2.4 Developmental Steps: Ideal Wing, Protoflyers and Inflated Flyers

To map differences in the set of requirements, the notion of progress in complexity was introduced by imagining five developmental steps within the set of requirements:

Step 1: providing lift

Step 2: balancing the forces of flight

Step 3: controlling the forces of flight

Step 4: providing volume

Step 5: providing propulsion.

The fifth step is not discussed in this chapter as it was beyond the scope of this work. Exclusion of this important body of work is justified as follows: The arrangement of the propulsion system is not considered part of the basic aircraft configuration but rather as a further elaboration imposed upon it or integrated into it. Furthermore, any aircraft in the domain under consideration should be viable in its unpowered mode (full engine failure as in an emergency mission segment or, deliberate deactivation as on a glider) and it must therefore meet all the requirements up to the fourth developmental step. This order of development allows consideration of externally added, integrated, retractable or detachable propulsion systems. In future work, the best strategy for propulsion (ideal propulsion) needs to be considered to find the ideal configuration at that developmental level. If this step requires a jump from one ideal configuration to another then the basic hypothesis would be significantly complicated. On the other hand, if ideal propulsion can be derived from the ideal unpowered configuration, the hypothesis stands stronger. At present, therefore, the central hypothesis is neutral on propulsion.

Ideal Wing

The rudimentary flight objective has no other requirement but lift. To define this flight objective, only the operational parameters and the performance objective are required. No statements about requirements for balance, control or volume are included. If the performance objective calls for minimum drag, then by definition, the global optimum would be the *ideal wing*. Therefore, the ideal configuration would be that of the ideal wing.

Protoflyers

The ideal wing solves only the first challenge of flight by providing lift with best aerodynamic efficiency. For practical flight, the forces of flight must be in balance and ultimately also controllable. The next developmental step in an imagined evolutionary progression from the rigid ideal wing must offer longitudinal balance. If the trait of control develops later, then strategies for stable balance must first emerge for flight to be practical. If the traits for control develop first, then active balance could be obtained by some advanced means of control. As control requires some type of flexibility and active control requires some form of sensing and feedback, active balance requires more than one step, while stable balance could develop directly. Therefore, the development of stable balance was considered the next important achievement after lift. The *rigid protoflyer* emerged when both longitudinal and lateral stable balance had been achieved. This would be known as the free-flight model, the ridged flyer that is by definition flyable without control. The next developmental step brings some kind of flexibility into the airframe to offer control over the forces of flight. With suitable modes of flexibility, the *controllable protoflyer* had thus emerged.

Inflated Flyers

Until now, there has been no requirement for additional volume. Economically practical flight revolves around payloads and the shape of an aircraft is most prominently influenced by the strategy by which useful volume is provided. While the protoflyer must be larger than its ancestral ideal wing, the most significant inflation comes from the requirement for volume for the payload and other bulky items of the flight apparatus. The inflated flyer is the aircraft that has taken the fourth developmental step to evolve the volume required for a given flight objective.

4.2.5 Evolutionary Family Tree of Configurations

When viewing the ideal wing as the common ancestor in an imagined evolution to the inflated flyer, new branches emerge at subsequent developmental steps given the diversity of strategies available to resolve each new challenge. Therefore, the aircraft design space can be arranged along these diverging lines or branches of diverse strategies into different species of inflated flyers, as illustrated in Fig. 4.3. The inflation factor serves as a measure by which the consequence of progress can be quantified and compared. Practical flight begins with any rigid protoflyer and further diversification can emerge given the variety of inflation strategies. In the following discussion, four of these lines will be explored on which *actual* implemented inflated flyers are found.

The ideal wing is specialised for lift at the lowest drag possible. This requires a cambered aerofoil for the best lift to drag ratio. In consequence, the ideal wing is unstable. However, when flying upside down it would be longitudinally stable as the camber becomes reflex when the aerofoil is inverted. It would be far from ideal as it would not be able to fly at the same operational parameters and its aerofoil properties are poor. If the reflexed aerofoil could evolve to be specialised for the same operational parameters, a slightly larger ideal wing would emerge, one that is longitudinally stable. It would be inflated due to having a larger surface area and even more due to a lower ideal aspect ratio.

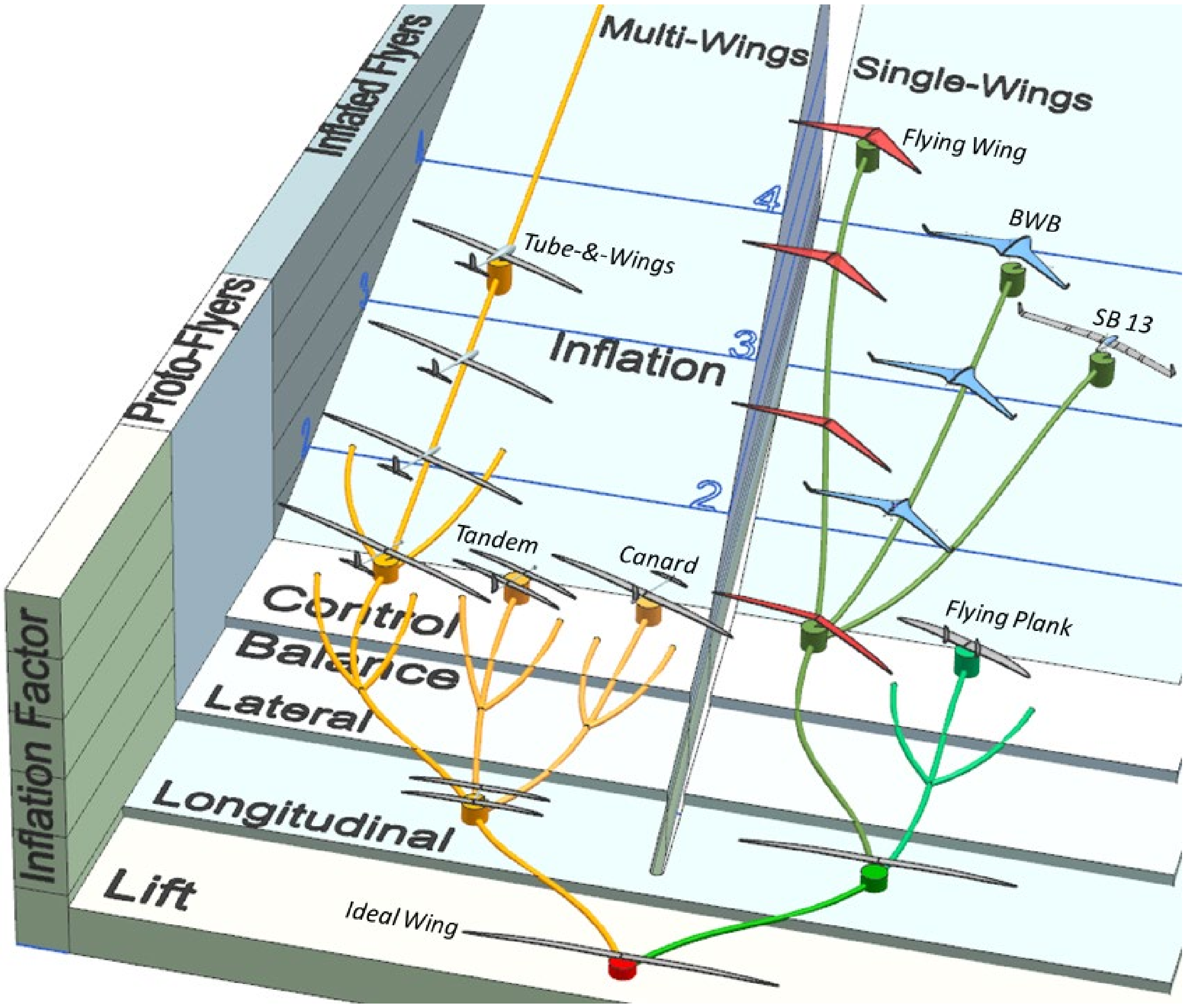

Figure 4.3 The imagined evolutionary family tree for fixed-wing subsonic flight with the performance objective of minimum drag. From the common ancestor of the ideal wing the tree branches off into the group of single-wing and mutli-wing configurations already at the first developmental step. The inflation factor gives a measure of how an aircraft enlarges as it evolves to meet more requirements. Using the example of a single-seat glider, four tried inflation strategies are shown for the two most prominent protoflyers.

Another way in which the aerofoil could evolve to be longitudinally stable while maintaining favourable lift-to-drag characteristics is by splitting off the reflexed portion along the span into a separate wing. The two longitudinally staggered wings require a joining structure. If these two approaches are seen as longitudinal stable descendants of the ancestral ideal wing then two distinct families have emerged, the family of *single-wings* and the family of *multi-wings*.

The next steps of also achieving lateral stability and then full control are first described for three descendants of the staggered wings. The aircraft record shows a few fully stable and controllable inflated flyers based on the tandem wing configuration in which a vertical wing is present on an extended boom of the joining structure for lateral stability and control. Furthermore, any form of proposed joined-wing arrangements could be seen as members of the tandem wing family.

Far more numerous in the current aircraft record are the descendants of the tandem wing in the branch of the canard family in which the rear wing is increased in size, specialised as the main lifting device, while the front wing is reduced to provide longitudinal stability and control. With the main wing now able to reach behind the centre of gravity, vertical wings can be placed at the wingtips for lateral stability and control.

The third branch of descendants of the tandem wing would be that of which the current dominant Pénaud arrangement is the fully stable descendant. In this family, the front wing becomes specialised as primary lifting device, while a long mass-balanced boom holds the small second wing rather far behind it for longitudinal stability and control. For lateral stability and control, a vertical wing is also placed here.

There are only very few descendants of the straight single wing in the aircraft record. Known as the flying plank configuration, their fully stable inflated flyers have evolved additional vertical wings for lateral stability and control. Pitch control is achieved by changes of the camber of the aerofoil with adverse effects on aerofoil properties as explained and illustrated by Nickel [5]. Among the very few flying planks in the aircraft record, the Fauvel family, including the AV22 and AV36 and the Pioneer mentioned in Chapter 3.4 are prominent examples.

Another strategy for achieving lateral stability on the single wing arrangement is to sweep the wings back. This strategy has many implementations in the records in aircraft based on the swept flying wing configuration, which can be seen as another fully stable descendant of the flying plank. The swept-wing form resolves the challenge for longitudinal and lateral stability simultaneously without the need for vertical surfaces. As an evolutionary development, the flying plank has evolved the articulation of the aerofoil either passive as for the free flight model or active in the controlled flyer. The evolutionary development of the swept wing has evolved articulation of the wing to yield a new planform. In the aircraft record within this domain, only passive planform articulation is found while control is also done by active aerofoil articulation.

The two most prominent competing protoflyers in the current aircraft record therefore are the Pénaud aircraft among the multi-wing arrangements and the swept flying wing among the single-wing arrangements, both capable of fully stable flight with rigid airframes or controlled flight after suitable articulations have evolved.

From many tried and proposed options, only four prominent inflation strategies leading to various inflated flyers are described below and illustrated in Fig. 4.3. The first strategy inflates the mass-balanced tail boom in the Pénaud family to lead to the tube-and-wings configuration, as the current dominant arrangement is often called. Another strategy inflates the entire wing, while another inflates only the central portion of the wing. These strategies are here applied to the swept single-wing by which the inflated flyer remains a flying wing or becomes a blended wing body aircraft. Another strategy brings about a single central discrete body on a swept single-wing protoflyer.

It would now be interesting to compare the tried strategies of development from the ideal wing to the different inflated flyers. However, before doing so a hypothesis is presented about the existence of a unique line of configurations, the line of a proposed family of ideal configurations.

4.2.6 Hypothetical Family of Ideal Configurations

From the work of Prandtl and Munk a century ago, it seems reasonable to propose that the global optimum design at the first developmental step, when only lift is required, is the ideal wing. Its configuration, just a single straight wing, is then the ideal aircraft configuration for that flight objective. Now the questions are: Which would be the ideal configuration for the rigid protoflyer (the free-flight model) and for the controllable protoflyer (for example, the radio-controlled model) and which configuration would be ideal for the inflated flyer? The core hypothesis of this work is that all these ideal configurations may belong to the same evolutionary line or family, the *family of ideal configurations*.

The hypothesis is formulated as follows:

There exists a single family of configurations, which holds the ideal configurations for the majority of flight objectives.

This implies that the best strategy for achieving the new function at every developmental level remains the best also in all successive developmental levels when this function is still required. In terms of the analogy with evolution, the most successful gene for a new trait remains in the gene pool in descendants within the ideal family. Given the large diversity of flight objectives, there will inevitably be special requirements that have their global optimum and thus their ideal configurations on other branches in the family tree. However, the majority of flight objectives have much in common, so that their optimum designs, when placed into the family tree may show clustering along a common line of configurations.

If this hypothesis has merit, it would have very important consequences. For example, in the search for the best aircraft configuration, one could compare strategies at the level of the free-flight model and the radio-controlled model to find the best family among the protoflyers. One could search for the best inflation strategy in fields of aviation with low economic risk before applying it to fields of high economic development risk. The following observations on the current state of aviation and on the basic principles of air transportation encourage a closer look.

Currently, a Single Family Dominates

It can be observed in practice that a significant majority of *all* flight objectives is being served by a single configuration, which must therefore be recognised as a dominant configuration. It rains as dominant since the middle of the previous century. It dominates at every level of development and over the spectrum of size from the free-flight toy to the largest airliner. This observation confirms that it is indeed feasible for a single family to serve a significant majority of all flight objectives in aviation.

However, it must be noted that a dominant configuration is not necessarily the ideal configuration for all or any of the flight objectives to which it is assigned. The fact that it is the selected arrangement does not in itself imply that it is the ideal solution.

Family Dominance is Expected

The existence of a dominant arrangement is not surprising because, for a given performance objective, the variations in the magnitude of the operational parameters may only affect sizes and proportions without requiring jumping between basic arrangements. This is especially likely when the set of different principal performance objectives is small, and in the space of all possible missions segments, there is often a close adherence to operate for either best range or longest endurance, each of which can be best achieved by the same arrangement of which only the proportions differ. Finally, the laws of physics governing flight are invariant and much commonality even in the details of solutions is thus expected. Commonality at configuration level would then be far more profound. Therefore, dominance by the same strategies with variations only in the details may be expected.

4.3 Comparing Tried Strategies

When tracing the variety of lines from the ancestral ideal wing to their inflated flyers, there is an inescapable decay in flight efficiency of the solution with growing inflation. The set of new genes which best preserves the ancestral efficiency would express the ideal configuration at any observed developmental level. The hypothesis suggests that such ideal genes will all be present in the best inflated flyer. *If this is true, then one only needs to identify the best strategy for balance and control and the best strategy for inflation to identify the ideal family of configurations*.

The hypothetical ideal wing offers best flight efficiency by allowing flight with best span efficiency on a flight body of minimum volume and best span. The developmental strategies have different impacts on the span efficiency, volume and best span. The aspect ratio of the ideal wing is the one that offers minimum total drag for the best viscous drag at a given Mach number and the consequential Reynolds number. Inflation will inevitably cause departure from the minimum size, directly quantified by the inflation factor. An increase in size inevitably comes with growth in material (together with carrier mass) and growth of wetted surface (together with viscous drag). When viscous drag increases, a lower aspect ratio will offer best total drag and this, in turn, has a profound effect on wing inflation, as equation 4.1 suggests. This can be beneficial if wing volume is useful, otherwise, it introduces redundant volume and thus a larger inflation factor in the final solution.

Mass is an operational parameter and is taken to be the same for the inflated aircraft and its ideal wing. With all-up aircraft mass being the sum of the carrier mass and the payload mass, less payload can be carried for the given all-up mass when more mass is needed for the carrier. The growth in carrier mass from inflation thus reduces the payload capacity. As a real solution is tailored for the required payload mass, a solution with a larger inflation factor will have a higher all-up mass than a less inflated contender.

Therefore, those developmental strategies which achieve their flight objectives with retention of best span efficiency and with the smallest inflation factor are likely superior to others. Consequently, one needs to compare the strategies only for their effect on the *span efficiency* and their impact on *inflation*. This will now be done for the two most used strategies of balance and control and four well-known strategies of inflation.

4.3.1 Tried Strategies for Balance and Control

When ideal circulation is induced along the span, the centre of pressure of this circulation distribution is called the E point [5]. For balance in the ideal case, the E point must coincide with the aircraft centre of gravity. For stable balance, the centre of pressure must move to restore the angle of balance in response to deviation. For control, the centre of pressure must be moved relative to the centre of gravity to produce controlling moments. The ideal strategy will allow the E point to be in the aircraft CG and will allow the ideal circulation to be retained or only minimally disturbed as flight angles deviate or as the centre of pressure is deliberately moved for control. The strategies for balance and control of the two fully stable and controllable protoflyers will now be compared.

Pénaud Protoflyer

The Pénaud protoflyer has the mass-balanced tail boom and the secondary wings of the empennage. One can here ignore the fact that the empennage itself can be arranged in a variety of ways, noting only that there are secondary lifting devices to provide vertical and horizontal components of force. These devices are not always productive but in the typical implementation, they are always present adding some mass and drag as reflected by some direct inflation. Some additional inflation of the main wing comes from the reduction in the aspect ratio due to an increase in viscous drag. In terms of the span efficiency, the boom will cause a disturbance of the ideal circulation. While this may be negligible for the small boom of the protoflyer, it is an inherent deficiency of this arrangement. Its strength comes from isolating the function of the main wing from the function of the stabilisers and the controls. In consequence, span efficiency is insensitive to deviations from the angles of balance caused by disturbances or inputs of control. Therefore, this strategy offers a robust and simple solution to the challenge of stability and control, but it introduces some undesired inflation. The critical question is whether this penalty is justified in terms of overall efficiency.

Swept Wing Protoflyer

The swept wing offers pitch and yaw stability without the need for additional features and no inflation is introduced by a boom or any vertical wings. Therefore, it is widely regarded as the purest aircraft arrangement, not deviating much from the ideal wing. This consideration motivated many developments throughout the history of aviation, offering solutions comparable with their Pénaud rivals. In their work, the Hortens found that the E point would not be in the centre of gravity if good handling qualities were given priority [5, 6]. Also, if wing-based controls are employed for change of balance, there is a direct adverse coupling between control and the circulation distribution, which can be detrimental to the span efficiency in off-design conditions [5]. Furthermore, most designers give preference to reflexed aerofoils, which have poor maximum lift coefficients. This introduces some inflation of the wing, not for volume but to meet the requirement for lift.

Perhaps the best arena for observable comparison of the two rivalling protoflyers is the contest by the radio-controlled gliders of the F3B class. Such aircraft are essentially without a requirement for volume. The flying wing has made prominent attempts to achieve superiority; however, so far, the Pénaud arrangement has prevailed in these contests [5].

4.3.2 Tried Strategies for Inflation

One may now imagine the evolution to continue from the protoflyer into species of different morphology as new generations incrementally advance inflation to provide useful volume. From a larger set of possible inflation strategies, four implemented strategies of historic significance are compared in the following sections.

Inflating the Boom of the Pénaud Protoflyer

In the Pénaud protoflyer, the boom serves only as a joining structure between the main wing and the secondary wings and for providing mass balance. As such it would be minimised in terms of volume to meet only the structural requirements. Given its availability and the need for mass balance, the boom is the obvious element to serve as payload container as it typically does in the current dominant configuration. It will now be discussed how this dual-function element influences span efficiency and redundant volume as the boom inflates to meet the demand for volume.

The boom length is dictated by the required location of the secondary wings and the requirement for mass balance. Therefore, inflation comes with the growth of diameter in some portions of the boom. With growing diameter, the boom occupies a growing portion on the wing, and the disruption of the trailing edge causes some

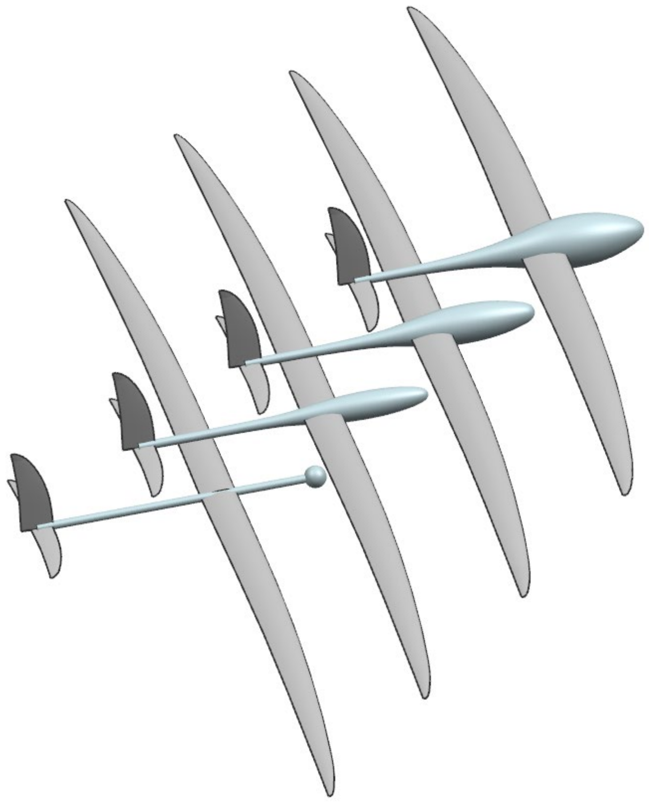

Figure 4.4 Boom inflation of the Pénaud protoflyer with reduction of wing aspect ratio and growing fuselage interference with the wing.

loss of circulation in that region. Some inboard vortex shedding must result and in consequence, the spanwise circulation distribution is adversely modified [7].

For reasons of mass balance, it is not always practical to use the aft part of the boom for payload and if one can, a balancing forward loading is required. This leads either to redundant volume or at least to a fineness ratio, which is not ideal in terms of viscous drag [8] and mass. The strength of this strategy is that it can offer virtually any inflation factor as demonstrated by extraordinary examples like the Beluga transport plane.

Inflating the Wing of the Swept Wing Protoflyer

While wing inflation can be applied to any protoflyer, it is here described as if applied to the swept wing protoflyer for which flying wings represent existing examples. Noting that the aviation literature is far less specific and not always consistent with the definition of the *flying wing*, it is here defined as follows:

The pure flying wing configuration consists of only a wing and shows no deviation from the principal geometry of the wing to provide additional volume or separate elements for stability, control, damping and trim.

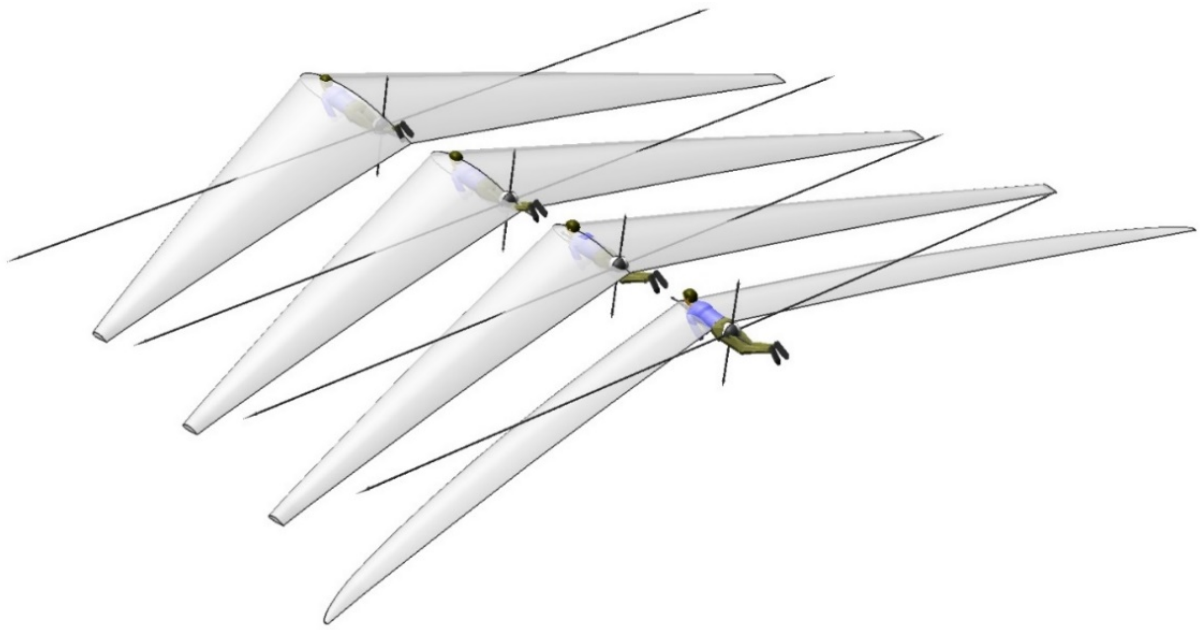

Figure 4.5 Wing inflation of the swept wing protoflyer to remain a flying wing until the volume is sufficient to enclose a pilot in the prone posture.

Initial small inflation can be accommodated by increasing only the aerofoil thickness and the original wing planform (and thus wing loading) remains unchanged and the increase in wetted surface is negligible. Further inflation will require distortion of the planform or scaling by which the wing size increases beyond the minimum of its ancestor. Wing loading lowers to suboptimal values, and the lower lift coefficients and aspect ratio no longer comply with the best C_L - AR combination. Now wetted surface grows rapidly with inflation due to the poor volume-to-surface-area ratio of an aerofoil, and the quality of the solution rapidly decreases. Furthermore, not all wing volume is practically useful and thus much redundant volume is introduced before being sufficient for the requirement. Therefore, the flying wing is not suitable for flight objectives requiring large inflation. This may explain why so few pure flying wings have ever been built.

Figure 4.5 illustrates the inflation of the swept wing protoflyer to remain a flying wing. The requirement for volume is strongly influenced by the relative grain size of the payload or other bulky items. The example illustrates a single occupant defining the requirement for additional volume. To show how ineffective this inflation strategy is, the occupant is placed in the prone posture, as the Hortens did with most of their gliders [6]. This posture needs less wing depth than that required by the more popular supine pilot posture, but even then, the redundant volume introduced is substantial.

The ideal wing is sized for the design lift and drag coefficients. Any growth of the wing beyond this ideal will thus reduce the required local lift coefficients all along the span, and retention of the original chord distribution is then no longer necessary. The ideal spanwise lift distribution can still be obtained by aerodynamic tailoring of the aerofoils along the span and the planform shape can be chosen in favour of more volume. It is then more practical to adopt the tapered wing as reflected in many historic examples. With the lower design lift coefficient, it is pointless to retain the high aspect ratio and thus the inflation of the flying wing is characterised by a reduction in span and taper ratio, as shown in Fig. 4.5. Even this strategy has hardly ever been taken to the full extent. To meet the grain size requirement, an additional deviation from the principal wing shape can normally be found in the aircraft centre. Even so, the resulting wing encloses a large volume, which has seldom been useful for more than the wing structure, the power plants and the fuel. Flight objectives involving high payload densities (like bombs) do not need much inflation and then the flying wing can be a suitable arrangement as demonstrated, for example, by the Northrop Y-49.

Inflating the Central Portion of the Swept Wing Protoflyer

To reduce the penalty of redundant volume incurred by inflating the entire wing to retain the flying wing configuration, a different strategy inflates only part of the wing. One such approach yields the blended wing body configuration. Again, because the literature applies this descriptor more casually, in this thesis, the blended wing body configuration is defined specifically as follows:

The blended wing body is an all-wing aircraft of which the wing is inflated for additional volume only in the central portion while retaining blended continuity of the wing leading and trailing edges and the upper and lower wing surfaces.

The central inflation would typically affect the wing chord, thickness t and area fraction f_{AF}, and the resulting aerofoil may be aerodynamically compromised in favour of the volume requirement. Therefore, it is rather called the body and no longer considered as being specialised as a wing. This body is blended with the remains of the ancestral wing, as shown in Fig. 4.6. An attempt can be made to shape the wing and body by design and to adapt them in flight such that the ideal downwash of the ideal wing is preserved. This requires that the wing should operate with very low local lift coefficients in the region of the body and its blends.

By this definition, many of the Horten aircraft like the H IX and even the H IV are actually blended wing body aircraft though they are typically referred to as flying wings in the literature [6]. Since wing inflation seems to dominate their inflation, as evident from their very low wing loadings [5], one could accept them as flying wings, albeit not pure. This example demonstrates that species cannot always be classified unambiguously, as the inflation strategies can also be combined in various ways.

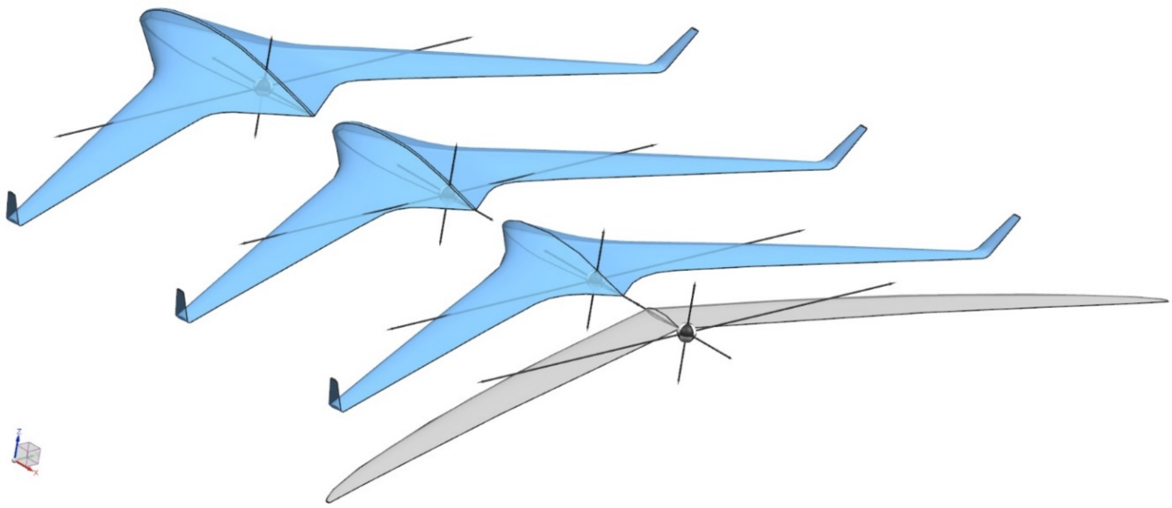

Figure 4.6 Wing inflation of only the central portion of the swept wing protoflyer to become a blended wing body.

The blend may introduce redundant volume, which will depend mainly on the relative grain size of the payload. Therefore, the blended wing body is not particularly suitable for flight objectives with large relative grain size like the pilot of a sailplane. Hence, it is mostly considered for larger aircraft when grain size becomes compatible with the depth of the wing [9, 10]. Therefore, this inflation strategy has poor general suitability.

Inflating a Discrete Body on the Swept Wing Protoflyer

If inflation of the central portion of the wing is achieved without retaining the aerofoil shape or edge and surface continuity, then another species emerges. Imagine the development of a dedicated central fuselage, which no longer preserves the form and function of the wing. Initial central inflation still yields the body blended with the wing until the continuities of the wing edges and the wing surfaces are broken. This inflation strategy can specialise the container around the payload for minimum mass and drag. For minimised drag, its fineness ratio will offer the best volume-to-wetted-surface ratio which separation-free pressure recovery will allow by terminating the body in a pointed trailing tip.

Torenbeek [11] refers to this as the discrete wing-cum-body arrangement in which also the wing can retain its specialisation as the lifting device. Stinton [12] would classify this under the *classical family* of arrangements having a distinguishable lifting device and a distinguishable non-lifting payload container as in the classical Pénaud arrangement. In contrast, the previous two inflation strategies would be classified into the *integrated family*. With separated specialisation of wing and body, inflation no longer has a direct impact on the wing geometry and the body can in principle be inflated to any scale without the penalty of redundant wing volume. However, the fuselage which thus emerges does not contribute to stability or lift. A body of the shape described is aerodynamically unstable and will not generate useful circulation. Balance must come from the wing, which

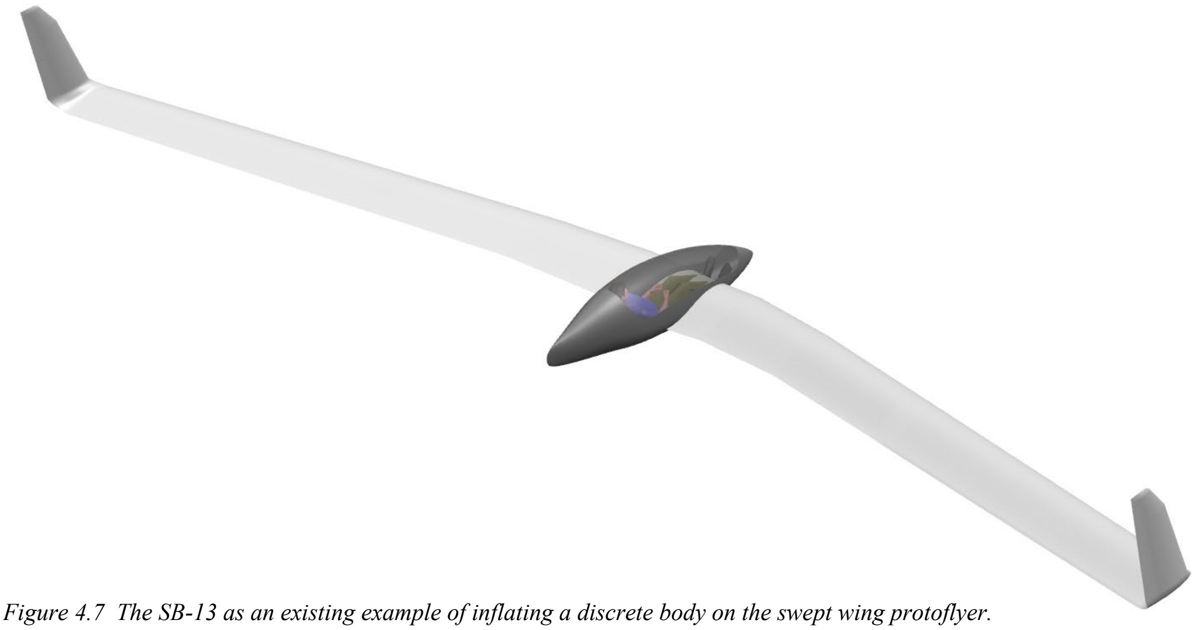

Figure 4.7 The SB-13 as an existing example of inflating a discrete body on the swept wing protoflyer.

will then have to grow with a growing body to compensate for the escalating influence of the unstable fuselage. This departure from the ancestral wing then introduces a penalty of redundant volume in the wing. Therefore, this inflation strategy becomes unattractive for large inflation factors.

The SB-13, shown in Fig. 4.7, a well-known representative of a discrete wing and body arrangement, demonstrates that passive stability at this inflation factor can still come from the wing alone. However, the challenging handling qualities of this aircraft [13-15] suggest that these proportions of wing and body may already be at the limit of acceptability. This may be a reason why further refinement of this specific design approach has proved difficult.

4.4 Considering Alternative Strategies

All the strategies described above have some deficiencies, as briefly summarised here. The inflated flyer of *Pénaud* does not fly with best span efficiency and is inflated more than would be necessary. The loss in span efficiency comes from the boom inflation and inflation is more than necessary due to the additional components already at the level of the protoflyer and later due to the emergence of redundant volume in the boom. The inflated flying wing has poor span efficiency and is not suitable for large inflations. Span efficiency is already poor at the level of the protoflyer due to the strategy of balance and control. Inflating a wing is a poor strategy because little useful volume is yielded while much surface area emerges. The blended wing body encloses some redundant volume and is not suited for payloads of large relative grain size. The discrete body on the tailless aircraft is shy of large inflation as it yields an unstable body. The typical strategy of control degrades span efficiency, already at the level of the protoflyer.

If one were to accept the Pénaud protoflyer to employ the superior strategies for balance and control, one may want to consider another inflation strategy to arrive at the inflated flyer. Junkers tried an inflated wing [16] and Burnelli tried the central wing inflation [17]; both approaches were without impact on the development of aviation. The discrete body inflation is very similar to that of inflating the boom. However, in the latter case, the ideal fineness ratio cannot guide inflation because the empennage constrains fuselage specialisation. If the Pénaud family is not the ideal family, then a different protoflyer will be needed. Recognising that its deficiencies relate to the boom and empennage, an alternative may need to be found in the family of the single-wings.

4.4.1 Alternative Strategy for Balance and Control

If the hypothesis is meaningful in that a single family would hold the majority of ideal configurations, and if the explored configurations are not ideal then the search for an alternative must start afresh at the ideal wing. One may have to reconsider the options to achieve the developmental steps towards the ridged protoflyer which is longitudinally and laterally stable. Furthermore, as the considered strategy of control of the single-wing seemed so problematic, another strategy for control may need to be considered for the controlled protoflyer.

If the swept wing is seen as a descendant of the flying plank in which aerofoil articulation had already evolved and in which then the trait of planform articulating emerged, perhaps the swept wing is simply a different posture of the flying plank if a central articulation had evolved. Perhaps other postures could be adopted if more articulations of the planform were allowed.

Consider a flying plank in which camber is articulated and which developed points of articulation along the span. The case, which has three articulations approximately equally spaced along the span, will now be considered. It can hold a longitudinally stable posture in the form of a flying plank by having a reflexed aerofoil, but it can also hold the posture of the swept wing where less reflex is required. In this posture, the structural centre has departed from the centre of gravity of the wing, which would introduce longer load paths into the structure in practical flyers. With the additional articulations available along the semi-span a planform can be obtained in which the structural centre remains in the centre of gravity of the wing while the longitudinal location of the wingtips can be placed in favour of lateral stability. Because such wing postures can be observed in nature this arrangement is here called the gull-wing form.

Any shape expressed in subsequent generations may then merely be a variant of the posture in the same family of configurations. If these articulations become active features, such morphing of the planform and the camber could serve as a more elaborate strategy of control.

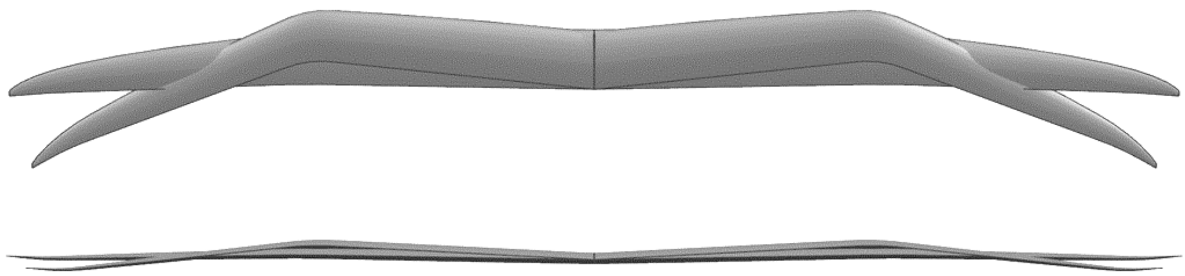

Figure 4.8 The ideal wing assuming a different posture to form a fully stable protoflyer in which the structural centre and the centre of pressure remain coincident. This is achieved by three (or more) articulations to change sweep and dihedral angles. The wingtip could have another pair of articulations. These can be viewed either as design variables or as variables under active control.

It is here proposed that the gull-wing form be recognised as a *special posture of the ideal wing* emerging in a descendent, which retained the ideal shape and size and which evolved appropriate articulations of camber and planform. *It may be that a specific posture offers acceptable stability, both longitudinal and lateral, and it may be that small in-flight changes of the posture may serve as useful elaboration for the strategy of control*. This certainly appears to be a promising alternative to the ideal wing fitted with a boom and empennage.

The remaining question is: Which inflation strategy may be best to maintain ideal circulation while minimising the growth of redundant volume to achieve even larger inflations? This strategy can take advantage of not being constrained by the presence of the boom and the secondary tail wings of Pénaud.

4.4.2 Alternative Strategy for Inflation

Inflation of the entire wing comes with a rapid decline in quality while inflation of only the central portion of the wing still introduced some redundant volume. Therefore, both approaches are unsuitable for flight objectives involving payload of large relative grain size. The discrete body and boom inflation strategy appear superior in terms of general suitability, but both disturb the span efficiency. The ideal strategy would allow independent body specialisation to any size without compromising span efficiency. Therefore, it may be helpful to return to the origin of this genetic line where the discrete body emerged to look for an alternative inflation strategy.

Consider again the emergence of a discrete fuselage, now on the proposed gull-wing protoflyer as shown in Fig. 4.10. Instead of emerging with a pointed trailing tip, the fuselage retains the wing trailing edge as it grows beyond it. Thus, imagine a low drag fuselage with a horizontal trailing edge (Fig. 4.9), which will hold the rear stagnation line to enforce the Kutta condition on the flow around the fuselage. A body with such a Kutta edge may perhaps induce a circulation about itself to provide downwash where the fuselage without it leaves a

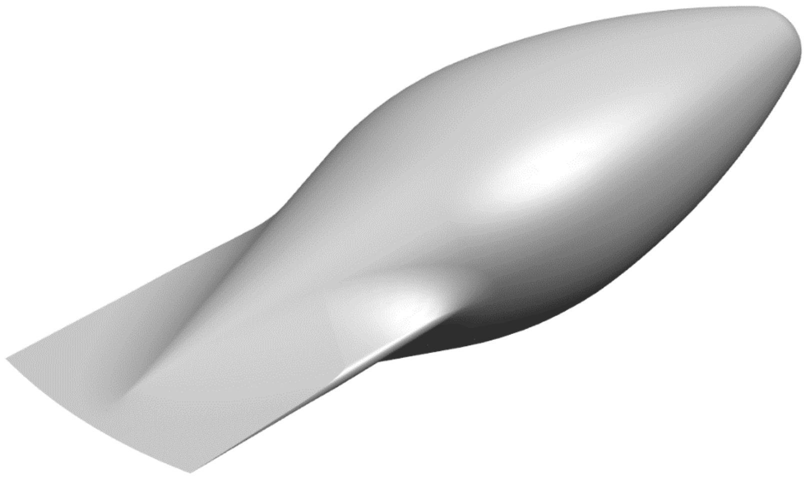

Figure 4.9 A body specialised in favour of mass and drag with a trailing edge, which serves to induce circulation over the body and to bring a neutral point onto the body. Such a stable lifting body could be inflated to any size while retaining its flight mechanic properties.

downwash deficiency instead. It would then be a lifting body by which the ideal span efficiency can be retained at any size. Another important consequence of the fuselage Kutta edge might be that it could bring a neutral point onto the body and with the centre of gravity suitably placed, pitch stability may be achieved on a fuselage of any size. Such a fuselage could be specialised around any payload in favour of mass and drag. If it is stable on its own at any inflation factor, pitch stability would not be demanded from the wing alone. The wing may then retain its ancestral qualities, still providing lateral stability and perhaps pitch stability of its own if necessary.

Such a configuration might be, like the current dominant configuration, insensitive to the inflation factor and it would be without the boom and empennage. Therefore, it might have even better general suitability. In principle, it might allow flight with the ideal downwash distribution in any flight condition. Its inflation would not be as large as that of its Pénaud counterpart and therefore its payload-carrier mass ratio would be superior. Such a fuselage would simply scale to offer the required volume as illustrated in Fig. 4.10. Strangely, there are no well-known examples of implementation of such a configuration in the aircraft record. This raises the question of whether the ideas proposed here could work as speculated and whether these could be applied to flight objectives in human aviation.

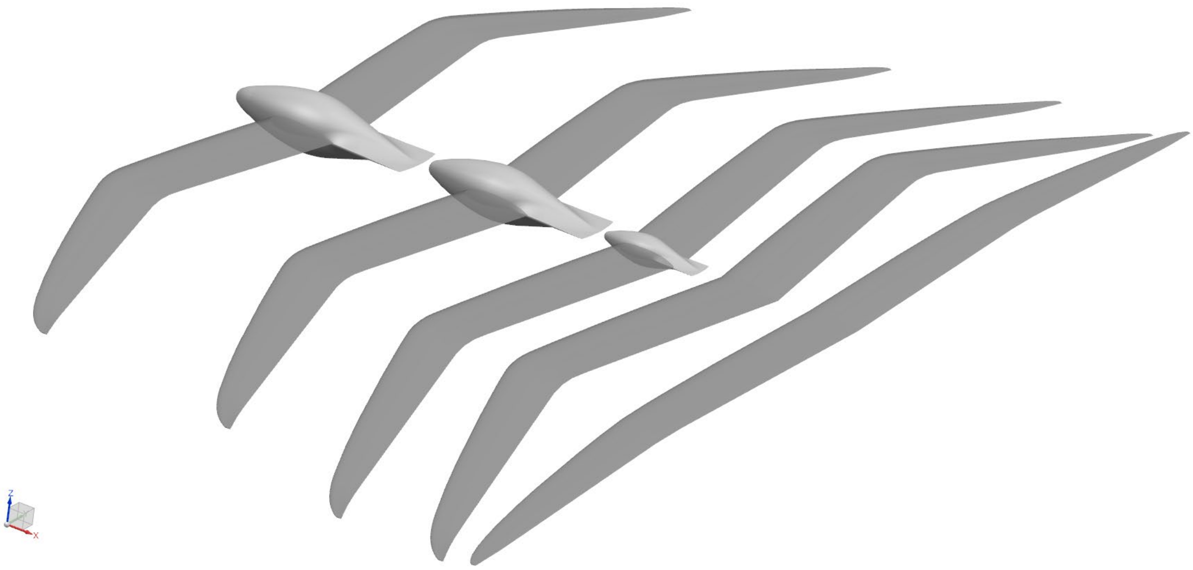

Figure 4-10 The ideal wing takes on a stable posture and then begins to grow a stable body to any required inflation factor.

4.4.3 Natural Dominant Configuration

As natural examples of rigid protoflyers, one finds seeds and among them also some for fixed-wing flight. Likely specialised for the performance objective of maximum endurance, the Zanonia seed is an example of a fully stable rigid protoflyer, which requires insignificant inflation for its payload (Fig. 4.11). Its wing shape has been tried in aviation in times when many aspects of the emerging art of aeronautics were still immature [5, 6, 18] and its failure to endure in the gene pool of aviation may not be linked to technical inferiority. Interestingly, the

Figure 4-11 The gull-wing morphology can be recognised in most natural gliders although these are genetically unrelated. The Zanonia seed represents a natural example of a free-flight model given that it is rigid and essentially without payload volume.

same wing morphology is also recognisable in other unrelated flyers in nature. If one expects, as implied by the hypothesis, the features of the protoflyer to remain present in its inflated descendants, then it should not be a surprise to find such features in the wings of bats, birds and pterosaurs, which can be considered as inflated flyers of this morphologic family. This morphology is currently perhaps most characteristically expressed in birds of higher wing loading, like many of the sea birds, and therefore, this wing arrangement is described as the gull-wing configuration.

Figure 4.12 shows the proposed gull-wing protoflyer and the proposed inflation strategy on the family tree. The best solution obtains its flight objective with the smallest inflation and with the best span efficiency. The figure shows single seat gliders designed for the same flight objective. All have been inflated until sufficiently large for a single pilot so that their relative level of inflation can be compared by the inflation factor as illustrated. It can be seen that the gull-wing configuration has the lowest level of inflation for the case of the single-seat aircraft. The larger member of the gull-wing configuration (top right in Fig. 4.12) is included to show that this strategy can accommodate even very large inflation like that of the Beluga of the tube-and-wings configuration.

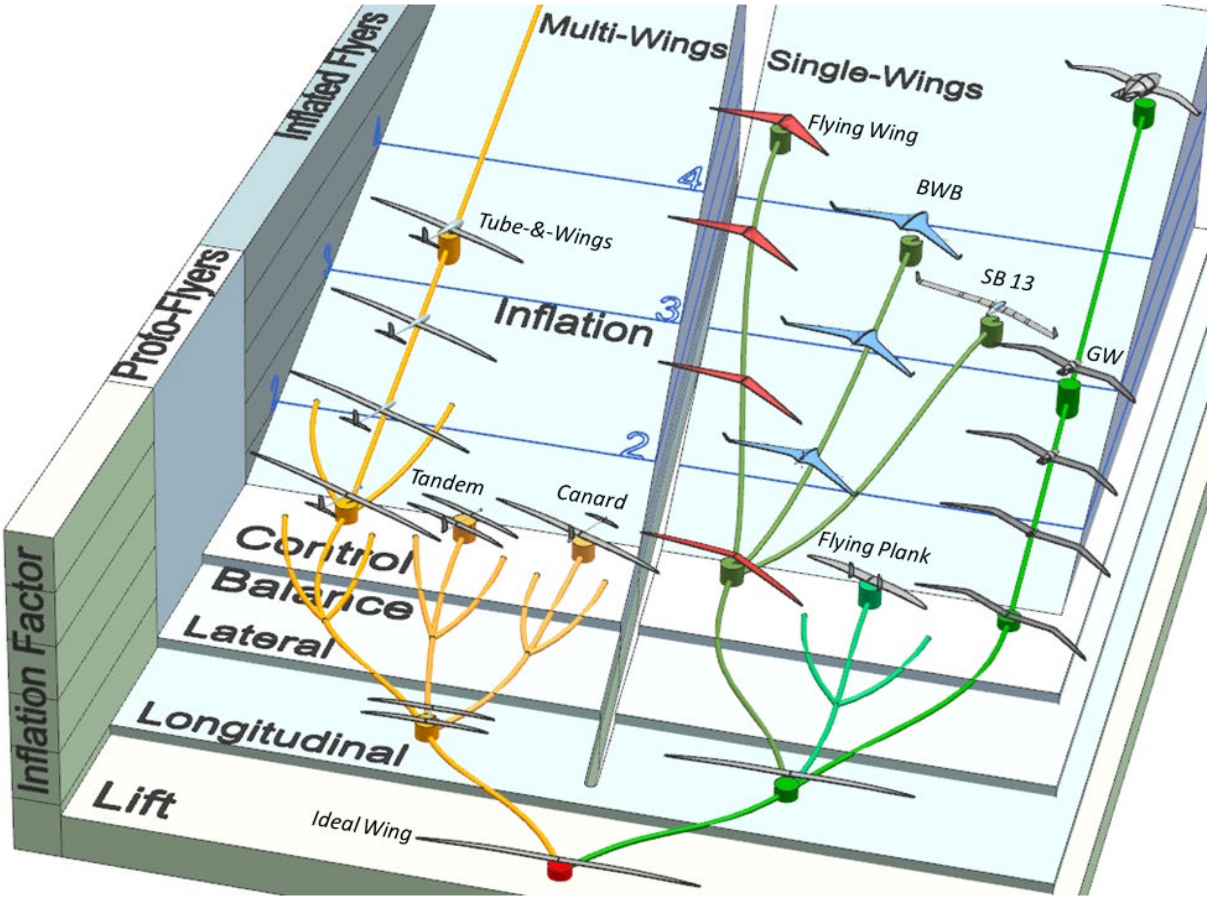

Figure 4.12 The family of the gull-wing configuration is shown on the right. The alternative protoflyer is just another posture of the ideal wing. Of all the inflated flyers it has the lowest inflation factor, not only among the single-wings but also lower that the tube-and-wings glider on the left. A very large inflation on the gull-wing is included to illustrate the insensitivity to inflation.

If the fuselage does provide circulation, also the span efficiency can be better than that of the Pénaud configuration.

Does this line perhaps represent the family of ideal configurations? All things considered, it is the dominant family in nature and if the hypothesis is true, then there should be only one dominant configuration in this domain, not two as is currently the case.

4.5 Conclusion

The aircraft design space was organised into an imagined evolutionary family tree while exploring the oldest question in aviation: What should an aircraft look like? The notion was proposed that most ideal aircraft configurations belong to one family, the family of ideal configurations. While it cannot be demonstrated that this notion is true, it has been demonstrated that it can be true and that it is rather likely to be so. Preliminary and qualitative comparisons of existing examples in the aircraft record confirmed that none considered were without fundamental deficiencies. Inspection of an alternative revealed the branch on which the natural solutions to the challenges of flight would be mapped on the family tree. This revealed a viable candidate for the proposed ideal family.

4.6 Recommendation

If a single aircraft family is indeed ideal for the majority of flight objectives and if the current dominant configuration is not the family of ideal configurations, then the priorities and structures concerning aircraft development ought to change accordingly. A better candidate must be found as a matter of urgency, and gradual implementation and refinement ought to commence as soon as possible. One could begin by exploring at the level of the protoflyer and one could search independently for the best strategy of inflation. One may apply any proposed strategy to any flight objective in the given domain and it is then sensible to choose a field of low economic development risk to give the new technology a chance to become established, refined, matured and accepted before applying it to flight objectives of high economic development risk. The protoflyers could battle out supremacy in competitions among free-flight models and in the arena of the radio-controlled gliders, perhaps in the class of F3B [5]. For the inflated flyers, the scene of gliding has often served as an incubator for new technologies in aviation [19]. It could again serve to test the ideas proposed here.

4.7 Outlook

While the above recommendations are beyond the scope of this work, the questions to which this initial exploration was dedicated are summarised as follows:

- *What does the ideal wing look like?*

This question has been explored on a theoretical basis as described in [1], presented as Appendix A. The notion of the specialised flight objective was also fully described and the parameter of wing density was introduced. In Appendix A, the binary divide among configurations is that which Stinton [12] proposed when he classified aircraft into the *classical family* and the *integrated family* rather than the single-wings and the multi-wings (as is done here). In [1], it was concluded that the aircraft configuration of the future would belong to the classical family, which has the dedicated wing and the dedicated body like the current dominant configuration has, rather than belonging to the integrated family in which the wing and body are integrated.

The main questions concerning the proposed protoflyer are as follows:

- *Could the ideal wing assume a special posture to meet the requirements for longitudinal and lateral stability to serve as an alternative to the Pénaud protoflyer?*
- *Could a hitherto unused additional dimension of control be useful when controlling wing wrist articulation?*
- *What would the handling qualities of an aircraft of this arrangement be, inclusive of static margin control?*
- *Does this arrangement present special challenges in terms of implementation or operation?*

Getting to terms with these questions constituted the bulk of this work, as described in Chapter 5, supported by Appendices E to I.

Further questions relating to the body of the proposed inflated flyer are as follows:

- *Does a non-lifting body on a wing actually disrupt the central circulation to cause a noticeable reduction in span efficiency?*
- *Can a trailing edge on a body enforce the Kutta condition on the body to induce circulation by which such deficiency can perhaps be restored or central circulation can be intensified?*
- *Would such a Kutta edge bring a neutral point onto the body to make the body stable on its own?*

The published work on this investigation is presented in Appendix C and summarised in Chapter 6. Finally, the features expected to be part of the ideal configuration are described in a patent, presented as Appendix D and summarised in Chapter 7.

4.9 Nomenclature

AR aspect ratio of the wing

BWB Blended Wing Body

C_L coefficient of lift of the entire aircraft

f_{AF} aerofoil area fraction, the fraction an aerofoil takes up within an enclosing rectangle

f_{PTE} planform transformation factor for elliptical planform transformation

FW Flying Wing

g gravitational acceleration, m/s^2

IF inflation factor, the ratio of aircraft volume to the volume of its ideal wing, Vol_{AC} / Vol_{IW}

m aircraft mass, kg

m_{PL} payload mass, kg

n manoeuvring load factor

N_{FO} number of all useful flight objectives (integer)

N_{GO} number of global optima of all useful flight objectives (integer)

N_{IC} number of all ideal configurations of all useful flight objectives (integer)

t aerofoil thickness as a fraction of its chord

V flight speed, m/s

Vol_{AC} total volume of an aircraft, enclosed by its wetted surface, m^3

Vol_{IW} total volume of the ideal wing, enclosed by its wetted surface, m^3

ρ air density, kg/m^3

4.10 References

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Chapter 5

Natural Dominant Configuration in Aviation

5.1 Introduction

In the foregoing chapter, it was proposed that a single aircraft configuration exists, ideal in terms of flight efficiency for the majority of flight objectives within the domain of fixed-wing subsonic heavier-than-air flight. It was hypothesised that such an ideal configuration should be a dominant configuration and that the domain should hold only one dominant configuration. It was noted that this domain includes the natural gliders of the pterosaurs, the birds and the bats, even seeds, with most belonging to the same morphologic family of arrangements of wings, bodies and means of control. Thus, in nature emerged a well-established dominant configuration, which is different from the current dominant aircraft configuration. It was pointed out that this natural dominant configuration has not been tried as such in human aviation and, therefore, the question remains whether it could work for the majority of flight objectives in aviation.

In this chapter, a preliminary broad-spectrum qualitative investigation of the proposed arrangement will be discussed. The earliest experiments used free-flight models to explore the flying behaviour in normal and unusual attitudes. Rigorous radio-controlled flying was done in demanding conditions with gliders and motorised models. Full-scale tethered flight testing was done with a pilot on board to explore the wing layout and the proposed strategy of control. Explorations focused on the proposed gull-wing protoflyer including pitch control by variable wing sweep. Work on the fuselage features of the inflated flyer will be discussed in Chapter 6. These preliminary tests did not require systematic measurements yet as they were intended to find hurdles before investing in refined quantitative studies. These tests would also show where further studies should be needed.

As far as the alternative protoflyer is concerned, no fundamental hurdles were found so far for which this arrangement and its strategy of control should be dismissed from use in human aviation. On the contrary, the findings encouraged further exploration and the expectation that the natural arrangement might eventually replace the current dominant configuration in human aviation.

5.2 Objectives of the Investigation

The objective of the work described here was to explore the flight mechanic properties of the proposed configuration to test their suitability in human aviation. Thus, the topic of stability and control, the handling qualities and the ergonomics of control received attention. Furthermore, some matters of practical implementation in terms of structure and operations were explored. This work did not investigate the issues of flight efficiency as it first had to be established whether the proposals could be practically implemented before attempts of refinement would be sensible. This means that no special attempts were made to optimise any designs in terms of efficiency, nor were attempts made to measure or compare performance parameters. The preliminary investigations present a qualitative assessment of a range of issues related to the proposed alternative protoflyer.

5.3 Scope of Work

The previous chapter concluded with an overview of questions to which this work was dedicated. Those discussed in this chapter are repeated here in more specific terms.

- Could the ideal wing assume a *special posture* to meet the normal requirements for longitudinal and lateral stability to serve as an alternative to the Pénaud protoflyer?
    - Could this be achieved by suitable articulations to provide special angles of dihedral and sweep?
    - What would such angles of dihedral and sweep need to be?
    - What stability properties could be achieved?
    - How would it recover from a stall?
    - Would this wing planform be suitable for camber changing flaps or cambered aerofoils?
    - Could such a posture hold the E point in the centre of gravity for stable flight?
- Could a hitherto unused *additional dimension of control* be unlocked by controlling wing wrist articulation?
    - Could the E point then be maintained on, or controlled around the centre of gravity?
    - Could an unassisted pilot sustainably operate the control of a wing sweep system?
    - What would the mass implications of such an added active wing articulation system be?
- What would the *handling qualities* of an aircraft of this arrangement be, inclusive of static margin control?
    - How would the aircraft respond to pitch control by elevon or by wing sweep angle?
    - Would this arrangement be prone to problems with pecking or pilot-induced oscillations or even the tuck?
    - Would the yaw and roll control couplings be problematic in terms of adverse yaw and Dutch roll?
    - Would a dedicated yaw control system be needed and how should this then best be implemented?
- Would this arrangement present special *challenges in terms of implementation or operation*?
    - What would the structural implications of the complex wing shape be?

- Could a normal runway take-off and landing be done?
- Could such an aircraft be launched by winch?

With the focus on flight mechanic investigations and on handling qualities, actual flight was preferred over wind tunnel work or numerical analysis but some wind tunnel tests and numerical analyses were also part of this investigation. These questions will be dealt with in the following discussion after describing the test equipment, the test results and the numerical investigations.

5.4 Test Equipment for the Investigation

Based on the hypothesis that a single configuration may exist, ideal for the majority of flight objectives, any flight objective could be chosen which presents special technical challenges to the practical implementation of the proposed configuration, while being economically feasible. It was thought that the most affordable actual flight tests could be done by free-flight models and by radio-controlled models. However, these alone would be insufficient to answer the questions concerning the pilot in the system. Given that many flight objectives in aviation rely on the unassisted pilot, unassisted both in terms of the control loop as well as the control work, such flight objectives would be more challenging than those in which a servo-assisted autopilot would control the aircraft. Because propulsion was disregarded in this discussion, gliders seemed suitable for much of this work. As the mass implications were of interest, the most challenging implementation might be in an ultra-light aircraft. And so, for full-scale implementation, an ultra-light single-seat glider was proposed, with radio-controlled models derived from this full-scale design.

Given the risk of flight testing of a new configuration, certain precautions needed to be taken. This required some special equipment to allow actual flight within the safe bounds of some test rigs.

5.4.1 Free-Flight Models

In preparatory investigations, small balsa free-flight models were used to examine the basic flying qualities of stable, rigid, tailless gull-wing protoflyers. The gull-wing posture was compared with a tailless simply swept wing posture and a conventional Pénaud protoflyer of the same scale. These models were typically hand-launched either indoors or outdoors. The centre of gravity and the outer wing twist were adjustable so that different trim and stability properties could be investigated in straight or curved flights. Some models were also launched at height from a radio-controlled glider to allow sustainable curved flight.

5.4.2 Radio-Controlled Models

The first radio-controlled flight tests were conducted with a 2.4 m span model, which had adjustable inner and outer wing dihedral and adjustable inner wing sweep. The outer wing sweep was adjustable also in flight. Geometric parameters for suitable static longitudinal and yaw stability and for an acceptable dihedral effect were identified by radio-controlled gliding flight in preliminary tests as described in [1].

Two further radio-controlled models (shown here) with a 3 m span were built for more rigorous flight testing. Sharing the same wing, two fuselages were provided, one for gliding flight and the other for motorised flight, both derived at ¼ scale from a full-scale design for a single pilot in the prone pilot position. Each wing had a servo for the flap, the elevon and the winglet and one to change the outer wing sweep angle. The glider could be launched by hand for slope soaring or by winch in a field and it landed on a single central landing skid. The motorised version for normal runway operations used an electrically powered tractor propeller in the nose and a fixed tricycle undercarriage with a steerable nose wheel. These models operating in the Reynolds number range of 250k to 600k are further described in Appendix E.

5.4.3 Exulans I, a Full-Scale Glider

As justified above, the investigations with a pilot on board were done in an ultra-light glider with tests in vehicle-mounted test facilities. To have some candidates for comparison, the relatively young category of Class II hang gliding was selected as the field of aviation as here the Flair 30 of Rochelt, the Aériane Swift [2] and the Ruppert Archaeopteryx [3] could serve as representatives of the simply swept tailless configuration and the Pénaud configuration. In terms of span, wing area, mass and thus wing loading, these three designs were very similar. Also the Exulans was designed for foot launching such that the pilot could carry the glider on his hips by means of a harness. When in flight, he could rotate forward into the prone pilot position. With both hands on a control bar, he could sweep the outer wings forward or back by swinging the control bar forward or back around a shoulder pivot in a motion similar to that which a hang glider pilot employs to move his weight for pitch control. In his right hand, he held a control stick by which the elevons were activated for pitch and roll control. The stick could also be twisted to open either the left or the right wingtip airbrake for yaw control (see inserted figure). The left hand had a handle on the control bar to help with the self-locking hydraulic wing sweep action. Therefore, both arms contributed when changing the outer wing sweep angle to anywhere between 21° and 36°. A pair of large flaps on the inner wings could be set by the left hand to any deflection between 50° down- and 6° upwards. The empty glider of 12 m span and 12 m^2 wing area had a mass of only 60 kg and with an all-up mass of 150 kg, it had a wing loading of only 12.5 kg/m^2. This would allow for vehicle operations at relatively low speed with the stall speed at test altitude only about 40 km/h. The Reynolds number would range between 600k and 2000k. The design of this glider is reported in [4] and some additional information about the glider and its wing sweep system is given in Appendix F.

5.4.4 Free-State Wind Tunnel

A vehicle-mounted test facility was used to fly the radio-controlled models in captive flight on the front end of a 3 m long articulated, mass-balanced boom. These tests allowed several of the investigations to be done under close observation and the models could be adjusted and qualified for real flight in a safe manner. This facility is described in Appendix G.

5.4.5 Pitch Test Facility

Investigations of the longitudinal stability and control properties of the Exulans I were done in the trailer-based pitch test facility in which the full-scale aircraft was held on its pitch axis with the pilot at the controls. An external operator could change its angle of attack and feel the pitch response to changes of the pitch angle and changes of the controls. This facility is fully described in Appendix H.

5.4.6 Vehicle-Mounted Tethered Flight Test Facility

The main full-scale flight experiments were performed on a vehicle platform mounted onto a small pick-up truck. Here, the Exulans I was free to fly within an envelope having a vertical and lateral extent of about 2 by 2 m, constrained by safety tethers while being pulled in its centre of gravity by a towline from a bowsprit on the vehicle. It would take off and land on the platform, controlled by the pilot for straight runs on a taxiway. In some tests, the vehicle would slowly swerve from side to side to allow lateral excursions. An operator at the front of the aircraft could perturb the glider in flight or steady it if necessary. An operator at the back would manage the tethers, keeping them slack within the operational envelope. This facility is further described in Appendix I.

5.4.7 Slope Soaring of the Radio-Controlled Glider

The main flight tests were done with the 3 m radio-control glider, hand-launched into the ridge lift of a brisk sea breeze (about 10 m/s) on a 100 m high coastal dune. Flight was maintained by flying figures-of-eight in the ridge lift with excursions away from the ridge for various experiments after which the model was returned to the ridge to regain lost height. In such excursions, circles were flown comparing the use of forward sweep to maintain the required pitch rate with that of using the elevons. Adverse yaw was studied with winglet/elevon mixing engaged or off. The long period oscillations were flown in stick-fixed conditions. Stalls were provoked and recovered. For some observations, an onboard video camera was looking from the fuselage at the wingtip so that the roll-yaw dynamics could be observed against the horizon. Other video recordings were made from the dune. Landings were done onto the single central skid on the sand.

5.4.8 Runway Operations of the Motorised Model

Normal take-offs and landings were made from tarred runways with the electrically motorised radio-controlled model with the tricycle landing gear. The electrical model with a tractor propeller in the nose had a steerable nose gear with adjustable spring damper suspension. Carbon fibre main struts of different stiffness were tested.

5.4.9 Winch Launches of the Radio-Controlled Glider

To determine whether this configuration was suitable for winch launching, a pilot experienced with winching of F3B radio-controlled gliders, launched the 3 m glider on an electric winch to a height of about 100 m. The objective was to see if any fundamental problems would present themselves for this kind of launching.

5.5 Tests and Results

Some of the tests with the models and the full-scale glider on the various facilities and in free flight are described here together with the observations made, the results obtained and the insights gained. The discussions which follow this description correspond with the questions asked in the previous section.

5.5.1 General Impressions

From the outset, beginning with the free-flight models and the initial radio-controlled model, the flying qualities always appeared satisfactory. The full-scale gilder and the radio-controlled models were easy to fly even in their unrefined state. The full-scale flying experiences on tether provided real excitement for all team members who had a chance to try their hand at the controls of this prototype. At the time, most of them had no prior flying experience but all managed to remain on target with ease. It did not require too much practice before the radio-controlled models could be flown vigorously within the envelope of the free-state wind tunnel by the pilot alone. On the dune, the sporty and responsive behaviour also made these experiences very pleasant. The winch launch of the glider presented no problems with the model pitching up rapidly and going into a stable steep climb. The only tricky experiences were had with the runway landings of the motorised model with its tricycle gear, as described below. Furthermore, compared with flying a model with a tail boom, it was more difficult to guess the aircraft attitude and therefore, slow flight was more difficult with these models.

5.5.2 Longitudinal Stability and Flow Separation

The early work with the free-flight models demonstrated that this wing posture could have longitudinal static stability in trim at positive lift given a suitable wing twist. The first radio-controlled flights confirmed this [1]. With the full-scale glider in the pitch test facility, the trim angles and the pitching moments could be measured for various elevon deflections, outer wing sweep angles and flap deflections. Of particular interest were the explorations of the pitching moments on and beyond the boundaries of the normal flight envelope. The question was whether the pitch response to flow separation would be violent or gentle and stable or unstable. The accident of the Flair 30 ultra-light tailless glider served as a concerning warning that dangerous flight conditions might exist at certain combinations of angles of attack and effective wing twist. To find the angles of attack at which separation would begin, to see where it would begin and how it would propagate, the glider was gradually forced to larger angles of attack, both positive and negative. Woollen tufts on the wing revealed flow reversal in areas of separated flow. The pitch response to separation was noted as separation propagated with growing angles.

It was found that stability prevailed favourably beyond the normal flight angles well into the separated flow regime. The pitch break would be described as stable. With the wings in separated flow, the elevons were deflected through their full operational range and were found to retain effectiveness without any control reversal.

To pitch the aircraft beyond the stall angle of attack without forcing it by an external moment, an upward elevon deflection was needed resulting in a rather large effective twist or washout, especially large when the inner wing flap was deflected fully down. Such arrangements led to separation over the inner wings with the flow at the wingtips still attached. The change in pitching moment resulting from separation was rather small but nose-down, as desired. In actual flight, this loss of lift would increase the sink rate, prevented here by the glider supports. These results suggested that the stall response should be gentle rather than violent and this was later confirmed in flight by the models.

5.5.3 Dynamic Stability and Stall Recovery

Among the flight tests with the 3 m radio-controlled glider, some stick-fixed phugoid oscillation tests were done. In one such test from straight and level flight, the elevons were pulled up and held fixed in a position that would trim the aircraft beyond the stall angle. The model would pitch up to an attitude of about 20°, climb and slow down, then drop the nose to about -20°, recover from the stall and climb again with a period of about 5.5 s between dropping the nose. The amplitudes of these oscillations were on the order of 10 m. In a similar test, the elevons were returned and held at neutral after a high pitch attitude was reached. The resulting oscillation was about 1 s longer with the initial amplitude of oscillation smaller and already hard to observe at the second cycle.

These tests also served to observe the stall recovery, which was found to be very gentle, without the nose dropping to a dangerous attitude. No tip stalls and therefore no spin were experienced during these tests. *All the results confirmed that robust longitudinal stability with satisfactory stall response can be achieved by this wing arrangement.*

5.5.4 Pitch Control

Flight tests with the 3 m model and with the full-scale glider on the vehicle showed that the elevons offered strong and rapid pitch response, suitable for light and responsive active control. Very tight turns were flown by banking the model glider steeply and pulling up the elevons. The low pitch damping of the tailless arrangement seemed favourable for such tight turns.

Tests in the pitch test facility confirmed that the static margin changed with the outer wing sweep angle as expected. Forward sweeping would reduce the margin, produce a nose-up pitching moment and a trim condition at a higher angle of attack. The nose-up pitch response by sweeping the hand wing forward was much slower than that of the elevon as the input actions were slower and, for the chosen stability margins and sweep range, the resulting pitching moments obtained were lower when compared with those obtained from the elevons at full deflection. Sweeping backward for a nose-down pitching moment appeared to have a slightly faster response than the opposite action. For mild manoeuvres like slowing down or speeding up or getting established in steady circling flight, wing sweep control appeared entirely adequate. Not only did this provide the required pitching moment, but it also established the new trim condition without elevon deflection. For continuous active control, it would be unsuitable.

When comparing the pitch control strategies during slow-down for landing (at the end of the tethered test runs), it was found that the touchdown speed was lower when the wing was gradually swept forward instead of pulling up the elevons while the wing sweep angle remained unchanged. This suggested that the effective maximum lift coefficient was indeed higher when the elevon remained neutral as predicted by Crosby [5]. This can be explained by noting that the upward elevon deflection increases the reflex in the affected portion of the wing to lower the local lift coefficient in that portion. The spanwise lift distribution is thereby compromised. When the wing angle of inner wing separation is reached, the outer wing has not yet reached its full potential which it would have without elevon deflection. Obtaining the nose-up pitching moment from the sweep change allowed the elevon to remain neutral or even downward deflected for a higher local coefficient of lift.

Unfortunately, no quantification can be offered here, because systematic data collection was not done during the preliminary tests when these observations were made. Also in line with Crosby's prediction, the flaps on the inner wing had no discernible influence on the pitching moment of the aircraft.

5.5.5 Ergonomics and Mass Penalty of the Wing Sweep System

The ergonomic aspects of the wing sweep system were tested in the pitch test facility where sweep actions could be performed at different attitudes under aerodynamic loads. While the airspeed was never more than

80 km/h, the pilot work load at speed was not noticeably higher than in static conditions. When used for slow manoeuvring and trimming, the self-locking sweep system of the full-scale glider did not place an unacceptable work load on the unassisted pilots, who operated the system. However, these pilots did not include males or females of small physical size or low physical strength and flights were of insignificant duration. Nonetheless, it was speculated, that the physical demand required to operate the sweep system would be acceptable to smaller pilots and over longer flights.

The embodiment of the sweep actuation system changed the position of the controls forward or aft. These changes did not present ergonomic problems of control for any normal flying condition. With the controls fully forward, using the control stick would be less comfortable, but this condition would not be held as a normal trim condition. It would only be temporarily used to induce a strong nose-up pitching moment.

An active articulation inevitably comes with a mass penalty which may offset the benefit it wishes to introduce. The wing sweep hinges added direct mass of bearings and inserts, all of which were steel components in this design. The actuators and their transmission and their locking elements added further direct mass. Two pairs of double-acting hydraulic actuators were used here with a pilot valve locking the output cylinder after a control input was given. Secondary mass penalties came from the larger safety factors which were required in control hinges, joints and linking elements and from the structure which needed to converge into load introduction points at the joints and links. It was estimated that the total mass penalty added up to about 6 kg, which a rigid wing of the same shape and free of the articulated joints could have avoided. It was still possible to build an ultra-light glider of only 60 kg empty mass to which the sweep system thus contributed about 10%. The joints in this system allowed for disassembly of the outer wings from the inner wings, a practical feature which one is likely to include even if the joints would be without articulation.

5.5.6 Pecking and Pilot-induced Oscillations

Of particular interest was the issue of pecking, an annoyance [6, 7] or even a threat on some tailless aircraft. Nickel and Wohlfahrt link pecking to the short-period α-oscillation and describe it as an unpleasant, violent and abrupt pitching motion around the lateral axis, one of the unresolved mysteries of tailless aircraft [8]. They suggest that it is specifically associated with gusty conditions and cannot be induced by the controls in calm conditions. If an aircraft is prone to pecking and if the period is unfavourable, it may lead to pilot induced-oscillation (PIO). As a dynamic response to a pitch disturbance, pecking may be associated with the phugoid oscillation, the long-period oscillation which follows the short-period alpha-oscillation (if one presents itself).

In the tethered full-scale tests, alpha excitations were either given by a step input by a large elevon deflection by the pilot, or by the front operator pitching the nose up or down and letting it go. For these tests, the pilot was either decoupled from the pitching motion of the glider, which pivoted on his harness in its centre of gravity or, with his feet resting in the fuselage, his inertia would be joined to the motion system. Different pilots had different preferences in terms of being coupled to or decoupled from the glider as this would either improve or impair their perceived quality of the pitch response. Whatever the preference, it seemed that PIO was only induced when aggressively provoked. Large alpha excitations were easy to induce given the low pitch damping but a short-period α-oscillation was not readily observable. A provoked excitation would damp out rapidly in a stick-fixed condition and there was no need for the pilot to actively respond. Sweep changes influenced the behaviour of the pitch response and a pilot could find comfortable settings to avoid those less comfortable to him. The radio-controlled models also did not show the phenomenon of pecking or a problem with PIO. Furthermore, within the speed range tested, no interactions with structural oscillations were observed in the tethered test facility nor with the models, but the author speculates and warns that such interactions are likely to occur at higher speed and these will be unique for every design.

5.5.7 Directional Stability and Damping

The preliminary work on this configuration by free-flight models demonstrated qualitatively that satisfactory lateral flight behaviour could be achieved. In straight flight, no yaw deviations or oscillations would be observed on a well-tuned model. In curved flight, a good balance between yaw and pitch rates would prevail so that well-coordinated turns could be flown. These early observations were of significance as they were done in comparison with models of the Pénaud arrangement and models of the simply swept arrangement. While no attempts were made to refine any of the models, it was noted that both the Pénaud and the gull-wing models had good and similar flight mechanic properties, while the simply swept models typically had issues with yaw oscillations like Dutch roll and spiral divergence in curved flight. The easiest models to get to fly well were always those of Pénaud, which were very tolerant to the position of the centre of gravity and which were easy to adjust by changes on the tail wings alone. These were also easier to launch. However, once a gull-wing model was well tuned, it would fly just as well although these would be less forgiving to a poor launch.

While exploring the topic of yaw stability, a model on a yaw pivot in a wind tunnel showed that the gull-wing in its tested form was statically stable in yaw, but the restoring moment would weaken with decreasing angle of attack. In these dynamic tests, yaw damping came in part from the bearing resistance which was absent in model flights and in the full-scale tethered flights. Therefore, yaw damping is described here, as observed in the tethered flights on the vehicle. During the pitch disturbance experiments, the onset of a slow yaw oscillation was occasionally noticed when large elevon inputs were given. The pilot did not perceive this as problematic, hardly noticing it in the absence of a proper reference to yaw excursions (the glider was not instrumented with a sideslip indicator or a yaw string). The pilot might often have been unaware of a yaw oscillation when not paying particular attention to it. However, when they occurred, yaw excursions were well observable from a distance, as from the chase car. The amplitude would reach up to ±10° and the periods were in the order of 6 s. Large yaw disturbances could not easily be given by the front operator, because pushing the nose sideways would displace the aircraft sideways rather than rotating it.

These oscillations confirmed that this arrangement was statically stable in yaw but revealed that yaw damping was poor. The pilot could use yaw control very effectively to arrest a yaw oscillation by deploying the forward-going wingtip airbrake. One or two such actions were typically enough to arrest the oscillation. However, in this first prototype setup, the yaw system was ergonomically poorly implemented. Activation of the tip airbrakes was achieved by twisting the control stick with the right hand to the one side or the other. The force required against transmission friction, return springs and the aerodynamic load made this very strenuous and as a result, the pilots preferred to neglect yaw control. This did not present a problem as yaw oscillations were not normally of notable amplitude and were perhaps often overlooked. With yaw control typically done by pedals, much stronger control inputs would be allowed in a system not activated only by hand.

Yaw stability and control were further explored by implementing winglets on the 3 m radio-controlled model. Comparisons could then be made in the free-state wind tunnel by flying with and without winglets. These tests confirmed that the yaw stability margin and damping were larger with winglets. Neither version seemed to have a problem with yaw oscillations. Video footage taken from the fuselage of the radio-controlled glider with winglets to observe the wingtip trace against the background did not show a notable continuous yaw oscillation. The winglets were steerable to allow yaw control. Therefore, the model without had no dedicated yaw control device unlike the full-scale glider, which had the tip airbrakes. Most flights with this model were done with winglets and their control was mixed with the wing sweep control so that sweep changes would not change the winglet toe-out angle. Aileron control was also mixed with the winglet to combine roll and yaw control. Therefore, the pilot would only control roll and pitch in normal flight.

5.5.8 Adverse Yaw

Of the five lateral coupling effects normally considered for typical aircraft arrangements, the yaw response to a roll input and then to the roll rate are of special interest. One important function of the typical yaw control system is that of counteracting adverse yaw, which is particularly noticed on aircraft of high aspect ratio. As the ideal wing is of high aspect ratios, the problem of adverse yaw may be a fundamental concern in the absence of the strong yaw control system. Therefore, special attention was given to observe the yaw response to roll inputs and roll rates.

During the tethered flight tests in a straight line, rolling moments could briefly be applied but only small roll excursions could be permitted. The roll response to such inputs far exceeded any yaw response such that the latter could not be clearly observed. For the exploration of the yaw response to roll rate, the glider had to be flown on a wavy trajectory, with the car swaying slowly from side to side on the 30 m wide runway. The pilot then had to change bank angle from about -15° to 15° as the trajectory inverted while following the car. Because the pilot had full control over the differential deflection of the elevons by combinations of pitch and roll inputs, it was found that well-coordinated turns could be flown without the use of the tip airbrakes and adverse yaw was not evident.

On the model, the mixing of winglet and aileron control could be deactivated in flight to compare the yaw response to roll manoeuvres with or without mixing. Video observations showed that both cases did not produce notable adverse yaw while rolling from about 30° to -30°. Even the aggressive flying of the model on the free-state wind tunnel without winglets and thus without any dedicated yaw control device showed no apparent problem with adverse yaw. Admittedly, yaw excursions were only visually assessed, which would conceal small excursions, but these would be of little consequence to flight efficiency.

The rolling moment from the typical rudder force was absent here as no typical rudder was present. However, if the winglets were used for yaw control, their deflection changed the lift distribution over the wing and thereby cause a rolling moment, and a slight adverse roll response to pure yaw inputs from the winglets would be noticed. In normal flight, this would be naturally compensated by a small roll correction.

5.5.9 Dutch Roll

Nickel and Wohlfahrt [8] list strong lateral stability together with medium to strong directional stability and low yaw damping as the three factors causing Dutch roll. The experiments which induced yaw oscillations showed low yaw damping but also showed that the skid-rolling moment (the dihedral effect) was small. Also, by side-slipping the model on the free-state wind tunnel, the dihedral effect was found to be small. The skid-yawing moment (the directional stability) would also not be considered as strong. This combination did not seem to cause Dutch roll and the phenomenon was never observed as such during these investigations.

5.5.10 Runway Operations

Tailless aircraft sometimes present challenges in terms of take-off and landing. Due to the smaller pitch inertia and the larger freedom to pitch excursions, the undercarriage may induce problematic pitching motions during take-off and/or landing. If strong aerodynamic yaw control is not available, the cross-wind take-off or landing may be challenging. Pitch authority may be insufficient to rotate an aircraft during take-off. Wingtip clearance is typically small and even reduces during rotation. Such issues were of interest when the motorised radio-controlled model was used to do taxi tests and flights from normal runways. Some interesting, concerning and surprising observations were made.

Low- and high-speed taxi tests were used to test the nose-wheel steering and to check for aircraft dynamics on the ground. Different stiffness properties in the wheel struts of the main gear and in the spring of the nose gear were tried. The arrangements tested would occasionally induce a roll oscillation, which was poorly damped and could even rapidly amplify during a ground run. Such oscillations would result in variations of the wingtip clearance, which appeared to be responsible for aggravating the roll excitation. If a roll oscillation did not occur, a normal take-off could easily be done but if an oscillation started, a take-off would better be aborted. The carbon fibre main gear strut of highest stiffness probably had a natural frequency in harmony with the roll mode of the aircraft such that a rapidly growing roll oscillation made a take-off impossible. The frequency was such that pilot compensation was not possible.

Once a wingtip would get too close to the ground, it seemed to be ‘sucked’ to the ground with opposite aileron insufficient to get it rapidly unstuck, requiring a take-off abort. This observation was recorded only once so that no conclusive comments could be made other than warning that the issue of wingtip clearance must be carefully further explored.

The stiffness and damping match between the nose gear and main gear suspension also seemed to be an important and challenging factor. With the main gear strut too soft, a hard-landing aircraft would sag down into the main gear with the nose gear then giving a pitch-up disturbance. This could cause the aircraft to take off again only to do a second, even poorer landing. A tailed aircraft under such conditions would probably touch down on the tail boom as well, thereby avoiding the nose-up disturbance.

Nose-wheel steering seemed very effective for directional control on the ground and due to the low yaw stability, the nose wheel had sufficient authority in crosswind take-offs. Elevator authority was sufficient to rotate the aircraft. With lift-off following immediately, there was then also no problem with yaw control after the nose wheel control authority was lost.

Perhaps the most problematic operational issue experienced throughout the test programme was the runway landing on a narrow model landing strip. The pilot reported that the absent boom made judgement of attitude and direction more difficult. This caused hesitation to fly the model slow and made lining up with the runway challenging. The resulting fast and misaligned landings then revealed the problems of the undercarriage, the low pitch inertia and the large pitch freedom.

While landing from the cockpit in the tethered flight tests had of course no such difficulties, the challenge of approach and landing should not be underestimated.

5.5.11 Winch Operations

During a winch launch, a high lift coefficient is desirable. This is typically obtained by pulling back on the stick which in the case of an elevon-controlled tailless aircraft means that the resultant wing twist is unfavourable for obtaining the best lift coefficient. The low yaw stability may present a problem. The structural loading on the wing is high resulting in some adverse wing twist on the swept wing. These were issues of interest when doing some preliminary winch launch tests.

The success of a winch launch depends largely on the placement of the winch hook on the glider. To find a suitable location for the launch hook, experiments were first done in water with a stainless steel model of the wing. These preparatory water tests gave confidence that winch launching could be feasible. A pair of hooks was then installed on either side of the glider model fuselage just below the centre of gravity.

The tests were done with the 3 m glider model, which had a single central skid with a wheel in the skid just behind the centre of gravity. The model was flown with winglets. An electric winch for launching F3B gliders was used in calm late afternoon weather conditions.

The test showed that normal winch operations could be done. The pilot, experienced with flying F3B models on this winch, reported no special concerns. However, this model was not comparable with the F3B models, which are structurally specialised to allow exceptionally violent launching. Such vigorous launches could not be attempted with this model. Also, the sweep system on this model was regarded as insufficient and was therefore not tried during these tests.

5.6 Results from Numerical Analysis

Two numerical investigations will be summarised here. The first concerns the investigation to find suitable angles of sweep and dihedral for the gull-wing protoflyer and to investigate variable wing sweep as a trimming mechanism. The second investigates the pitch handling qualities of the gull-wing protoflyer.

5.6.1 Sweep and Dihedral Angles and Variable Wing Sweep for the Gull-Wing Protoflyer

From work done on this project, Crosby [5] reports on the use of a three-dimensional source patch and ring vortex (SPARV) panel code to estimate the most important lateral stability derivatives, the dihedral effect and the yaw stability. He found that the requirements for the best dihedral effect and for best yaw stability tended to be in opposition to each other, however, an acceptable combination could be obtained. He found that 3° of inner wing dihedral with 6° of forward sweep and 7° of anhedral on the outer wing with sweep back between 21° and

36° would give the best combination of parameters. The forward sweep of 6° would be needed to yield an inner wing centre of pressure position, which would minimise the change in pitching moment due to changes of inner wing camber or flap deflection. He predicted that yaw stability would be low but acceptable in the absence of vertical surfaces. His results did not include the contribution from differential viscous drag, which would make a small positive contribution to yaw stability.

He also used the SPARV panel code to estimate the difference in induced drag when trimming a tailless wing of the gull-wing shape by means of the elevons or by variable wing sweep. He demonstrated that the latter can offer a better circulation distribution, which was not disturbed by the elevon deflection. The improved span efficiency reflects in lower induced drag especially of interest at low speed. The better circulation distribution also offers a better maximum lift coefficient for the wing, which can in consequence be smaller than that trimmed by the elevon. The smaller wing reflects in lower viscous drag, especially of interest at higher speed. Together, better overall efficiency can be expected if trim control comes without the disturbance of the circulation distribution.

5.6.2 Pitch Handling Qualities of the Gull-Wing Protoflyer

In work done on this project, Agenbag [9] analysed the longitudinal handling qualities and the gust response of the proposed wing form using the Exulans I design as an example. Special interest was given to the question whether the E point would reside ahead of the neutral point such that stable trim could be achieved together with good span efficiency. The other important question concerned the tendency for pilot-induced oscillations.

Handling qualities were studied using the Neal-Smith analysis technique [10] and the gust responses were evaluated using the Mönnich-Dalldorf criterion [11]. The Cooper-Harper pilot rating scale was used as a reference [12]. Modelled gust responses of the Exulans I were also compared with those of the ASW19 conventional sailplane having good handling qualities and the SB-13 tailless sailplane having problematic qualities.

This study predicted that a region of centre of gravity locations existed for this wing layout for which the aircraft would have both satisfactory handling qualities and good span efficiency. Problems with pilot-induced oscillations were not expected for this design and it appeared that the aircraft should have acceptable handling qualities in gusty flying conditions. Interestingly, the results suggested that lower static margins would result in better handling qualities in gusty conditions and flight at low air density and higher static margins would present poorer qualities.

The publication of this work is attached as Appendix B.

5.7 Discussion

5.7.1 Special Posture of the Ideal Wing

All experiments and theoretical studies confirmed that the basic wing could assume a special posture to offer satisfactory longitudinal and lateral stability properties to serve as an alternative to the Pénaud protoflyer. This could be achieved by suitable articulations to provide special angles of dihedral and sweep. While many more options were available, only the option with three articulations was investigated and already found to be suitable. This was experimentally explored before quantitative evaluation suggested the combination of wing angles reported above. Implementation and testing of the full-scale prototype and the scaled radio-controlled models confirmed that a suitable compromise between the dihedral effect and directional stability was obtained. The arrangement had robust pitch stability, even into the regime of separated flow, but yaw stability and damping were low but acceptable. Together with a low skid-roll coupling (the dihedral effect), the arrangement was free of the tendency of Dutch roll.

Stall recovery was observed to be gentle and this could be related to the specific posture. Nickel and Wohlfahrt [8] explain that a loss of local lift from flow separation further off the lateral axis through the centre of gravity will have a larger change in pitching moment and thus a stronger pitch response than the case where the local lift is lost closer to the lateral axis through the centre of gravity. The gull-wing posture has its inner portion very close to the lateral axis through the centre of gravity. Therefore, if separation begins here, as it seems to do, a milder pitch response occurs.

In this posture, the structural wing centre and its centre of pressure can be made to coincide. Even the wing centre of gravity may be close to this structural centre. This implies that the structure in the wing root during normal flight only carries a bending load without a large chronic torsion load.

In the proposed posture, the wing is insensitive to the camber of the inner portion so that cambered aerofoils can be used as seen on natural wings [13] to offer better maximum lift coefficients. In this posture, the E point is predicted to reside ahead of the neutral point such that stable trim can be obtained together with good span efficiency. The location of the neutral point for the given wing planform does not change with camber, but the centre of pressure does.

The centre of pressure of the ideal camber distribution, the E point must coincide with the centre of gravity to be in balance for best flight efficiency. As long as speed varies with lift coefficients rather than wing loading, a variation in camber can be compatible with the coefficient requirement. In slow flight, for which large lift coefficients are needed, a suitable large camber can be used on the inner portion of the wing. In fast flight, a reflexed aerofoil is suitable because the lift coefficient does not have to be high. The aerofoil variation along the span between the two conditions may be rather small so that a small camber variation at the trailing edge of the aerofoils may suffice. It would be beneficial if the effective twist distribution along the span were tailored in favour of the circulation distribution for every desired trim condition, but then, balance must be obtained by selection of the required static margin.

Therefore, it is speculated that the ideal wing in this special posture, if applied in human aviation, will employ strong camber as part of an active twist distribution control system that tailors the twist to maintain the best span efficiency. Variable wing sweep (or some other form of static margin control) will have to help to maintain the balance. However, special care will have to be taken to avoid the tuck, which is assumed to be a risk associated with the low pitch damping and the strong camber and large effective twist for low-speed flight.

The landing accident which terminated the development of the Flair 30, which first flew in 1990, was cause for specific concerns. The Flair 30 employed large landing flaps, which might have been deployed when a nosedive occurred while on the landing approach. Accident investigators proposed that lower surface flow separation at the wingtips might have prevented recovery from the nosedive, which might have been caused by a nose-down elevon input to speed up during the approach. This pitch response, perhaps a tuck, happened too close to the ground, resulting in a fatal impact. The control settings assumed to be associated with this accident were carefully explored. On the Exulans, with the elevons deflected fully up while the landing flaps were fully down, the wing had a very large effective wing twist and was never in trim (with a nose-up moment remaining at all angles). It never showed a nose-down moment even when forced to a negative angle of attack for lower surface separation at the wingtips. However, a nose-down elevon control input had a very fast response. An unbalanced elevon could easily aggravate the control input due to the control surface dynamics such that the associated trim condition would be at negative lift. If the resulting nose-down pitch rate is fast and perhaps a negative lift scenario occurs, the risk of an unrecoverable attitude may be high. While failure to recover from such a negative lift condition was not experienced in the pitch test facility, it is advisable to pay further attention to this risk in any design. Downward elevon deflection as elevators should perhaps be constrained to smaller angles to avoid too fast nose-down responses. This may perhaps be best achieved by the elevator gearing to the control stick, which will yield a smaller downward deflection when the stick is at the forward limit. Furthermore, control surface mass-balancing needs proper consideration. While it would appear that the gull-wing posture might be less vulnerable to such a tuck, it is here strongly recommended that such investigations be repeated for any new design.

The change in the dihedral angle at mid-semi-span is sometimes referred to as a wing crank. In their book on tailless aircraft [8], the authors call it the 'Weltensegler-crank', referring to the gull-wing glider by Wenk of

1921, the Weltensegler. They comment that while such a crank is typical on wings in nature: 'the "crank" of most bird wings at approximately half of the semi-span has neither structural nor aerodynamic significance but results, rather, from the requirement that the wings can be folded away'. However, they later asserted that it offered a reliable means to prevent Dutch roll and to reduce adverse yaw and it increased yaw damping. This author adds that pitch damping and inertia are also increased slightly. While birds have active control over more structural articulations including their shoulder and wrist joints to allow almost any wing posture, the posture assumed during gliding flight is not unlike that found here to give useful longitudinal and lateral stability properties. This author speculates that this is no coincidence.

5.7.2 Static Margin Control

The tests with the radio-controlled models and the full-scale glider offered practical demonstration that static margin control could be unlocked by controlling wing wrist articulation. Numerical simulations [9] confirmed that the E point could then in principle be maintained on, or be controlled around the centre of gravity. If used for trim control in conjunction with elevon control, suitable combinations should be obtainable such that wing twist is ideal for span efficiency while the aircraft is also in balance at that condition. Handling qualities change and can thus be adapted in flight to be suitable for the given conditions. For example, simulations predicted that a lower static margin appeared more desirable in gusty conditions and a pilot could then adapt the airframe accordingly to suit the conditions.

Continuous circling presented no problems and for small bank angles, the required pitch rate could be obtained with the wings swept forward. For steep bank angles, forward sweeping alone was insufficient for the given centre of gravity location and additional elevon deflection was needed for the required pitch rate. Given that the effective wing twist changes on a swept wing when a pitch rate is applied, a twist adaptation will be required to maintain the desired circulation distribution. Such additional wing twist may therefore be desirable.

If the forward limit had a smaller sweep angle, or if a smaller static margin were used, a very fast nose-up pitch response would result from sweeping forward into the unstable domain. This strategy can be observed in hunting birds like swifts [14] and should result in more effective and efficient rapid turning. In aviation, such requirements are probably mostly of interest in some fields of sports aviation, particularly in radio-controlled flight.

Assessment of the physical work required for wing sweep changes suggest that an unassisted pilot can sustainably operate the control of a self-locking wing sweep system. While no long flights were ever performed to confirm this, the system of sweep control was compared with that of a hang glider in which the pilot uses weight shift continually both for active pitch and roll control without the benefit of a self-locking feature. By this comparison, the use of self-locking variable wing sweep for trim control requires significantly less control work. For continuous fast active control, the unassisted system as here implemented will not be suitable as it has too much flow resistance in the hydraulic transmission, but for occasional fast control actions like the landing flair the system can be used.

It is speculated that even on larger and heavier aircraft under unassisted control, a manual wing sweep system can be implemented for trim control. When servo control takes care of sweep changes, the ergonomic concerns disappear. The sweep hinges in a wing together with their activation system are comparable to the wheel support and activation system of the front wheel of any car, a complexity that all users are quite willing to accept in terms of operation, maintenance and reliability, also in the version with power steering.

On aircraft where the principle mission does not require fast or frequent trim changes, other means of static margin control may be preferred. On an airliner, for example, active wing articulation may be unnecessary if instead fuel, water or cargo can be relocated to maintain ideal balance.

The mass penalty of the wing sweep system, estimated at about 10% of the empty mass of the ultra-light glider, has to be compared with the penalty which a mass-balanced tail boom and the empennage will bring to a wing if the Pénaud arrangement is the alternative. Comparing the empty mass of the refined Swift tailless glider (48 kg) and the refined Archaeopteryx Pénaud glider (54 kg), both designed for the same category of gliding, one may assume that the empennage and boom mass may be reflected in the difference of 6 kg thus being of the same order of magnitude as the sweep system penalty of the unrefined Exulans. If this penalty may help to make up the difference in performance of inferior minimum sink and glide angle of the Swift (a simply swept tailless design with wing-based controls for trim), then the tailless aircraft with static margin control may be a viable alternative to the Pénaud solution. One may also consider that a refined wing sweep system may come with a smaller penalty than that of a first prototype and every designer should consider the alternatives to variable wing sweep for static margin control for a specific design. These results only suggest that static margin control can be done even by an unassisted pilot, it can be useful, its mass penalty is not overwhelming, and it may help resolve the shortcomings previously disrupting the serious development of single-wing aircraft.

5.7.3 Handling Qualities

While the numerical investigations offer some quantitative estimates on this topic, perhaps the most important contribution from this work comes from the actual flight experience gained from the aircraft built for this assessment. Therefore, this discussion focuses on the actual flight experiences, adding only that the theoretical evaluation [9] essentially advise that the longitudinal handling qualities are expected to be satisfactory and flight efficiency does not have to be compromised on their behalf as was often done with other tailless aircraft.

Handling qualities can be described by unified rating scales, and the Cooper Harper rating scheme [12] was employed here. This scheme rates a feature in one of four categories with a pilot rating between 1 and 10 with 1 being highly desirable and 10 the score for an uncontrollable aircraft. In this assessment, the focus was on the desirability of the flight mechanic responses rather than on the quality of the prototype mechanisms in the control system, which offered ample room for improvement of the details of their designs.

The task for which the pilot had to offer an opinion was that of a typical gliding flight, which would typically require the management of flight in an active atmosphere but would not require special precision of flight. The mission segment of flight in rising air is of special interest. However, the full-scale glider was only flown in the tethered flight test facility in rather calm conditions. Only the radio-controlled model was flown in very turbulent conditions in the ridge lift of a dune. This discussion merges the experiences from all the tests into single ratings for pitch, roll and yaw control and for the sweep system.

The procedure and terminology described in [12] are briefly summarised in Appendix J.

Pitch and Roll Response by Elevon – Satisfactory –PR 2 (good)

Pitch and roll control was light and responsive giving quick and easy authority over the full flight envelope. The turn could be introduced and executed by the single control of the elevons. It took only little practice to get the coordination right and adverse yaw did not present a problem even without active yaw control. Perhaps the Weltensegler-crank made the contribution explained by [8], namely that the anhedral on the sweep back hand wing combined with elevon deflection would produce a yawing moment in the desired direction. No aircraft tested seemed prone to pecking or pilot-induced oscillations or Dutch roll. The nose-down pitch response should be further investigated to ensure that appropriate elevon deflection limits apply to avoid an excessive nose-down pitch rate.

Pitch Response by Wing Sweep – Unacceptable – PR 7 (major deficiency)

If variable wing sweep were to be used as the only pitch control mechanism in its tested state, then adequate performance would not be attained because there could be flight conditions in which the control input and its response would not be sufficiently fast. For the purposes of primary control, the active sweep range would have to be increased to allow larger control moments to be attainable and the control resistance to fast motions would have to be significantly reduced. While this could in principle be done, variable wing sweep would certainly not be recommended as the only mechanism for active pitch control.

Pitch Trim by Wing Sweep – Satisfactory – PR 3 (fair)

In its role as a pitch trimming mechanism, the sweep system performs its task satisfactorily. The mildly unpleasant deficiencies are that the work required is more than that of other systems and that in this embodiment, the controls move to different positions with retrimming because the control stick is on the sweep lever, which is moved back and forth for trimming.

Yaw Response by Tip Airbrake – Satisfactory – PR 3 (fair)

The mildly unpleasant deficiencies are that the response for the tested size of tip airbrake is slower and less effective and that it requires more work to actuate when compared with a typical rudder. Normally, yaw control is done by the feet of the pilot and this would also be the preference here. However, with the feet of a foot-launchable glider temporarily unavailable, the yaw controller was given here to the right hand instead. It is of course entirely feasible to also give yaw control to the feet during flight so that much stronger muscles and larger displacements are available to do far more control work easily. Then also a more responsive tip airbrake can be employed.

Yaw Response by Winglets – Satisfactory – PR 2 (good)

Winglets were only employed on the 3 m radio-controlled model making their assessment in free flight only observable from a distance. However, close-up observations could be made on the free-state wind tunnel. The yaw response seemed good with the negligible deficiency that a slight adverse roll coupling would result from winglet activation alone. However, this was easy to override with a roll input and because yaw and roll would typically be given together, one would not normally notice the adverse roll. For normal flight with the winglets, the control of winglets was mixed with the roll control so that the pilot would do lateral and directional control only with a roll and pitch input.

5.7.4 Winglets

The natural flyers do not employ winglets and it is evident that the natural wing posture offers static yaw stability without them as was made apparent by several of the tests described above. Without winglets, the yaw damping was low. Moreover, the stability margin seems to reduce with decrease in angle of attack (increase in speed). Yaw oscillations were not self-induced and thus not normally present, though in turbulent air this is likely to be different. When occurring, such oscillations were easy to arrest by causing a small opposing imbalance at the tip of the wing, in this case using the tip airbrakes. The frequency was low enough about 0.17 Hz for synchronised pilot compensation.

The winglets provided good passive yaw damping and a stronger, non-dissipative means of yaw control. However, given that the low damping without presented no significant problem, it may not be necessary to add the complexity of steerable winglets. Unless kept very small, these require a stronger wingtip and a higher torsional wing stiffness. They are vulnerable elements given that wingtip contact with the ground is common in some fields of sport aviation.

To use a dissipative concept of control, such as the wingtip airbrake, is not in principle desirable in terms of flight efficiency. However, when arresting an oscillation from the onset, only insignificant interventions were required. Compared with a permanently exposed damper, like the vertical fin of the Pénaud arrangement, this retracted feature presumably accumulates lower losses over a mission even if it is drag-based. This would probably not be the case if continuous active yaw suppression was needed to suppress Dutch roll but this configuration did never showed the tendency for Dutch roll. The tip airbrakes were never needed to counter adverse yaw.

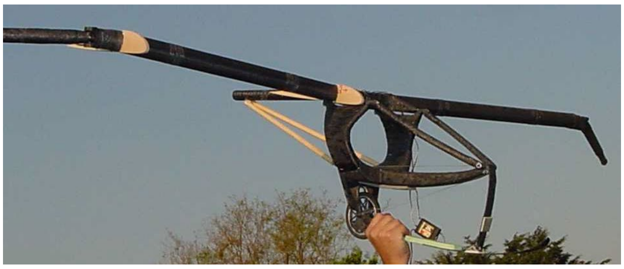
Therefore, a designer may choose against winglets unless required for other reasons. It may be desirable in early phases of development to have a more robust means of yaw control and better damping. Likewise, in cases where asymmetric thrust may occur, good yaw authority will be needed. As always, if span limitations are imposed, winglets will be desired to increase the effective span.

The author expects that the development will converge towards designs without permanent vertical winglets. These will perhaps rather be found in the form of level wing extensions, in some cases perhaps to be raised into an upright posture in flight to serve some special temporary demand. The wingtip plays an important role in stability, handling and control (roll, pitch and yaw). The geometry must serve the objective of preventing local separation there, and in this configuration, the wingtip plays the role of the empennage of the Pénaud configuration, hence rendering the tail plane assembly redundant. As such, the level winglet, as it may be called, does not need to be part of the productive span over which the ideal circulation distribution should extend. It would meet design requirements more in line with ideas proposed by Prandtl [15], Horten [16] and later again by Bowers [17], who talk of the bell-shaped lift distribution. And, if not fully occupied by other roles during normal cruise, it may serve to further improve the span efficiency. The author speculates that the success of the gull-wing arrangement will have much to do with the role of the wingtip. Therefore, it should be the subject of future investigations.

5.7.5 Structural Challenges

Compared with the straight unswept wing of a typical Pénaud arrangement or the simply swept straight wing, the gull-wing arrangement is structurally more complex, because the sweep angles cause to introduce a torsion load in the inner wing by the bending load from the outer wing and sufficient torsional resistance and stiffness must be provided. By designing, building and operating such a wing, some challenges could be practically experienced.

In the full-scale ultra-light glider, the inner wing torsion box was provided by the nose of the aerofoil together with the main spar to form a D-box, and thus it served the dual function of carrying the torsion load as well as serving as the wing skin. This approach led to a rather sensitive structure at risk of torsional buckling of the wing skin. While it would quite easily carry normal flight loads, the large wing skin here had to be made tolerant throughout to in-flight impacts (like bird-strike or hail) and ground handling traumas. This made it much heavier than normal flight loads required it to be. With the D-box a flight-critical element of the primary structure at risk of losing integrity from small local damage, significant redundancy had to be provided to avoid being compromised by likely operational adversities. Also, special care had to be taken at all times when handling the delicate structure and proper inspections were needed if some form of trauma occurred. While such penalties may affect many aircraft structures, here the sensitivity to torsional buckling of an exposed wing skin needs to be recognised as a special risk due to the torsional load being larger than that of a straight wing.



Recognising this deficiency, a different approach was followed in the next design by providing a round tubular main spar responsible to carry bending, shear and torsion loads while no longer serving as the exposed wing skin. Therefore it was an independent internal structural element protected from in-flight impacts by the non-critical wing skin and it is no longer exposed to the risk of unrecognised ground handling damage. While this concentrated structure was much smaller and therefore required more wall thickness, it made for an overall lighter and far more robust or damage-tolerant structure. Such an arrangement also dealt far more effectively with the load path concentrations as found in the sweep hinges and wing joints, thereby reducing the mass penalty of the wing sweep system. Such dedicated structural elements would also be easier to test and certify. This approach was implemented in the wing structure of the 3 m radio-controlled model and found to be superior to the previous approach.

Transitions in the dihedral angles at the root and the wing wrist presented no special difficulty for the primary structure, it only added some complexity to the wing skin mouldings at the wing wrist.

5.7.6 Operational Issues

The runway operation tests suggested that this arrangement presented new challenges for the development of the undercarriage. Regardless of the field of application, such a task should be expected to be more challenging than for aircraft of larger pitch inertia. This challenge should be considered when developing the fuselage flap as this offers the opportunity to provide another contact point in the tail of the aircraft.

The first winch launch tests done here only showed that winch launches could be done. It must still be established if they can be done with performance on par with the current best aircraft. It would then be interesting to see if the correct trim condition could be obtained by static margin control rather than by distorting the wing by the elevons. For the configuration to be superior to that of Pénaud, it must ultimately also demonstrate superior winch launch performance. This may be a crucial qualifying test for the proposed configuration. To win, for example, F3B flight competitions by overall better performance, it cannot be inferior to the tailed configuration during winch launch as the simply swept rigid tailless alternative apparently is [8]. This flight phase places special demands on the wing structure and its load distribution and it is important to see whether the proposed arrangement will meet these demands.

5.7.7 Closing Remarks

The early work with the free-flight models demonstrated three important aspects when these were compared with the dominant Pénaud protoflyer and the much tried simply swept tailless protoflyer. First, similar flying qualities could be achieved with the gull-wing and the Pénaud arrangement, but, second, it was much easier to achieve these with the Pénaud arrangement. Third, the qualities of the simply swept models always appeared less satisfactory. This may have had an important implication for the development of aviation. The simpler solution, the one easier to get right, has a better chance to become dominant. No evidence stands out that the gull-wing configuration had been tried at free-flight level with any consequence to the development of aviation. In contrast, the model of Pénaud has left a noted historic mark. When it comes to flight efficiency, the ease of arriving at a good solution may be less important than the quality of the solution. It is in this spirit that the quality of the proposed solution should be further explored.

Together with many other aspects which will be new to a designer, it is expected that the design of an aircraft based on the proposed configuration will be substantially more challenging. However, the difficulty of design will gradually disappear as the pool of collective experience increases. To grow experience in design and operation, the F3B gliding competitions will offer a suitable arena for comparison with protoflyers of the current dominant configuration and with conventional tailless aircraft. The violent winch launch will be an important challenge in this comparison. The flight envelope can here be further explored with special attention to spinning, pecking, the tuck and the tumble. At the same time, the proposed configuration can be compared with the traditional form in the sport of gliding. If it is indeed superior, it should ultimately win over the current arrangement.

The wing form for transonic operations will require new work to find wing angles suitable to delay the onset of local shock waves. The details of the wing posture may be different from those derived here. It is quite likely that the posture may remain rather similar to the current art, which is not far from the posture recommended here. However, the function of the empennage must be transferred to the wing in as far as the fuselage requires this.

5.8 Summary

Experiments on full-scale and radio-controlled protoflyers showed that this arrangement was very promising for use in aviation. The wing posture recognisable as dominant in nature offered good stability properties both longitudinally and laterally. It allowed camber on the inner portion of the wing where flow separation would then initiate with a moderate stall response. Handling qualities were satisfactory with very effective elevon response, without adverse yaw pecking or pilot-induced oscillations presenting problems. Though winglets were tested, the low yaw stability without them seemed acceptable and if occasional yaw control inputs were needed, tip airbrakes seemed sufficient. The arrangement did not appear prone to Dutch roll or the tuck. Trimmed flight and pitch control could be achieved through combinations of outer wing sweep and elevon deflection such that isolation of control of circulation and control of balance seemed feasible. None of the practical tests considered thus far, from sharp pitching in flight, venturing into separated flow, to runway or winch operations, nor the structural challenges on the airframe, indicated any major problems in advancing this novel configuration. On the contrary, all design objectives appeared to be achievable with this arrangement. When combined with previously discussed performance advantages, there is a compelling case for further development.

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Chapter 6

Wing-Body Circulation Control by Means of a Fuselage Trailing Edge

6.1 Background

The exploration of the aircraft design space presented in Chapter 4 described various inflation strategies to provide useful volume to a protoflyer. The preferred strategies were identified but found to degrade span efficiency because the fuselage on the wing modified the central downwash induced by the wing. The proposed alternative inflation strategy required that the fuselage should contribute to circulation to avoid this central downwash deficiency. It was speculated that a trailing edge on the body could force the rear stagnation line such that the body would induce some circulation over itself. It was also speculated that such a body edge could bring a neutral point onto the fuselage to offer the possibility of longitudinal stability for the body. These speculations had to be carefully tested. The findings of the main experiments were published under the title above and this chapter offers a summary thereof with some additional remarks to put the investigation into the context of this thesis. The publication [1] is presented in Appendix C.

6.2 Introduction

When scrutinising the different inflation strategies for providing useful volume for the payload or other bulky items of the flight apparatus, it appeared preferable in terms of general suitability to inflate a dedicated body on a dedicated wing. This approach led, to what Stinton [2] calls the classical arrangement. The fuselage of the Pénaud configuration which developed by inflation of the tail boom appeared superior in terms of general suitability because it could offer the largest inflation. However, it could not take advantage of the best fineness ratio for the body because its length was compromised by the requirements for holding the empennage and for providing mass balance. On the other hand, the discrete body emerging on the stable single-wing did not have this constraint and could therefore emerge as a scalable body specialised in terms of mass and drag. In that respect, it appeared superior to the inflated boom, which enclosed more redundant volume, thus having a fineness ratio suboptimal in terms of structural mass and viscous drag. However, the tailless inflation strategy did suffer a limitation on allowable inflation, because the emerging body lacked own stability, which the empennage would otherwise provide. Both bodies would cause interference with the central wing circulation, thereby harming the span efficiency.

The proposed alternative strategy also produced a dedicated discrete fuselage specialised for mass and drag but it retained the wing trailing edge when inflating beyond it. This should hold the rear stagnation line to enforce the Kutta condition on the flow around the fuselage, thereby inducing a circulation about itself to provide downwash where the fuselage without it leaves a downwash deficiency instead. It would then be a lifting body by which the ideal span efficiency could be retained at any fuselage size. Furthermore, if the Kutta edge would bring a neutral point (or region) onto the body, own pitch stability could be achieved on a fuselage of any size when the centre of gravity was suitably placed.

6.3 Problem Statement

While one may readily observe the proposed strategy in natural inflated flyers like the bird, the literature describing the functions of the bird tail [3-12] does not include descriptions to the effects proposed here. Furthermore, no convincing reference could be made to existing work to describe the effect of a fuselage on the spanwise circulation distribution of a wing occupied by a prominent typical fuselage, the best perhaps shown by Hoerner [13]. Furthermore, concepts of stabilising fins are well established for bombs, torpedoes, airships and other such bodies in motion. However, these are normally not expected to contribute to lift or serve in partnership with a wing and their movement of the centre of pressure is not of great importance. Therefore, it seemed necessary to conduct some own experiments to test the speculations at the core of the proposed inflation strategy:

- *Does a non-lifting body on a wing disrupt the central circulation to cause a reduction in span efficiency?*
- *Can a trailing edge on a body enforce the Kutta condition on the body to induce circulation by which such deficiency can perhaps be restored or central circulation can be intensified?*
- *Will such a Kutta edge bring a neutral point (or region) onto the body to possibly make the body stable on its own?*

6.4 Preliminary Experiments and Analysis

To assess the merit of the speculations about stability and body circulation, it seemed prudent to do some preliminary experiments before committing to the elaborate wind tunnel campaign. As this work is not included in the publication of Appendix C, it is briefly described here.

Water tests were conducted on wooden bodies, symmetrical about their two axial planes, without and with a trailing edge. In the first set of tests, the position of the centre of pressure was tracked by holding the fuselage on a pitch axis in various longitudinal locations when moving the body through water. This demonstrated that for the body without the trailing edge, no placement of the pitch axis on the body would yield a stable pitch balance with symmetric flow. This confirmed that such a body would make no useful contribution to aircraft stability.

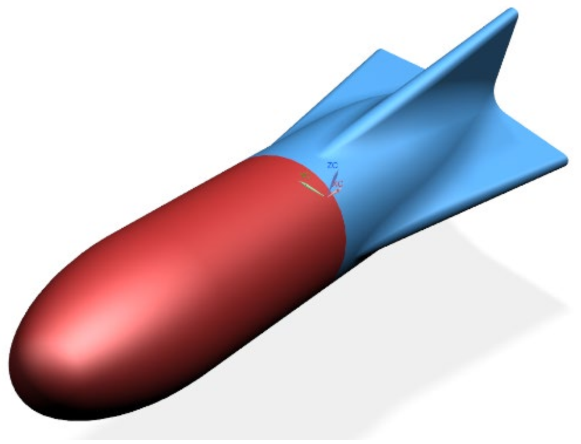

Figure 6.1 The body used for the CFD analysis to simulate the 600 mm long 5 kg ballistic projectile.

Reshaping the aft body to terminate in a horizontal trailing edge would allow a symmetric zero-lift flow condition and would bring a neutral 'point' onto the body. With the pitch axis sufficiently far ahead of this neutral region, the symmetric body would be in stable balance around the zero angle of attack. It was assumed that the flow dynamics would equally apply to the flow of water and air, such that the observed stability would also apply to a body in the air. This assumption was tested in free flight with a projectile that was pneumatically launched at 43° and 20 m/s onto a

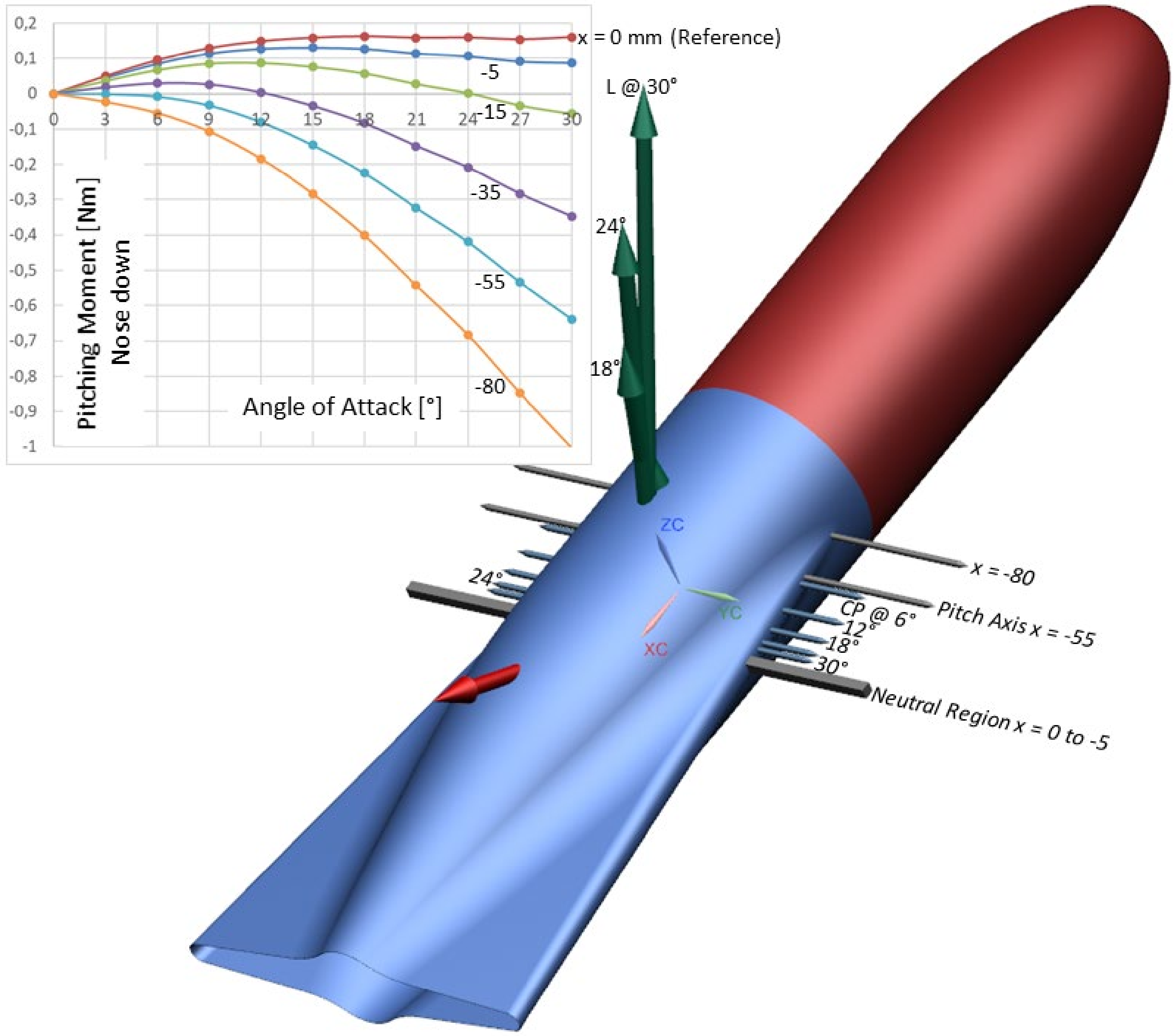

Figure 6.2 illustrates CFD predictions of the position of the centres of pressure, the lift and the pitching moments at different angles of attack relative to a reference (x = 0). It can be seen in the graph that the pitch curves between x = 0 and 5 mm are rather constant at higher angles of attack so that this can be declared a neutral region. With the axis more than 55 mm ahead of this reference, the body is stable around the 0° angle of attack, though restoring moments are very small at small angles but rapidly increase with a deviating angle. Locating the centre of gravity 80 mm or further ahead of the neutral region, gives a fully stable flight body.

parabolic trajectory. This wingless body (5 kg, diameter 100 mm, length 600 mm) was fitted with horizontal and vertical trailing edges comparable with those shown in Fig. 6.1. These tests confirmed that the wingless body was stable in the air in pitch and yaw for the selected position of the centre of gravity. Employing CFD analysis of the projectile of Fig. 6.1 predictions were made by Crosby of how the centre of pressure would move with changes of the angle of attack (between 0° and 30°) to find out if a neutral point could be declared for such flow interactions. Fig. 6.2 shows the pitching moment curves for various pitch axis locations. It can be seen that within a small region of locations, rather constant pitching moments prevail at higher angles of attack so that this region can be viewed as a neutral region. Technically, this does not qualify as a 'point' but for practical considerations, the region is sufficiently small (shown to scale by the bar from x = 0 to -5 mm in Fig. 6.2) that a neutral 'point' can be declared. Then, as long as the pitch axis is ahead of this region, a stable pitch response results.

In the next set of preliminary experiments, the wake behind a wing-body arrangement was observed while moving only the wing and then the wing with the body through water first without and then with the trailing edge while the wing-body arrangement was held at various lifting angles. A rail and dolly above the water provided repeatable conditions of motion of which the surface wake could be observed photographically. Comparison of the surface wake images showed clear differences in the wake signatures. One could even interpret the wake formed without the trailing edge to show the downwash deficiency of the wing-body combination. However, these preliminary tests lacked the means of quantification, which the main set of experiments was designed to provide.

6.5 Flow Visualisation in the Wind Tunnel

With the preliminary tests showing early signs of confirmation, it seemed reasonable to invest in a more elaborate test campaign. These tests utilised the technique of correlation imaging velocimetry [14], by which the flow field behind a wing-body arrangement can be made virtually visible in an array of observation planes. A large array of flow vectors was gathered in parallel *x-z* planes behind the model. The data were then processed in search for up- and downwash and vorticity. A large matrix of tests was conducted in which the angle of attack was varied for different aft body and trailing edge deflection angles, while the rectangular wing was always rigged on the body at the same angle (6°) and the speed of the tunnel was always at 10 m/s at sea-level density. The aft body could be set at different angles and different plates could be fitted to try different deflections and trailing edge shapes. These tests were conducted in the low turbulence low-speed closed-loop wind tunnel of the University of Southern California.

6.6 Results

Of the large array of data collected, the necessary confirmation could already be declared after post-processing the data of only one angle of attack. In this case, the body was aligned with the flow and, with the wing rigged on it at 6°, the wing angle of attack would also be 6°. The results of only one trailing edge plate are described, with the aft body set at 0, 4 or 8°. As a reference, the wing would be tested at first without the body, then the body would be added and run through the different aft body deflection angles but at first without the trailing edge plate. Thereafter, the trailing edge would be added to repeat the tests. These results were sufficient to show that the downwash responded uniquely to the trailing edge deflection angle (and width) as is shown in a sample set of pictures in Figure 6.3.

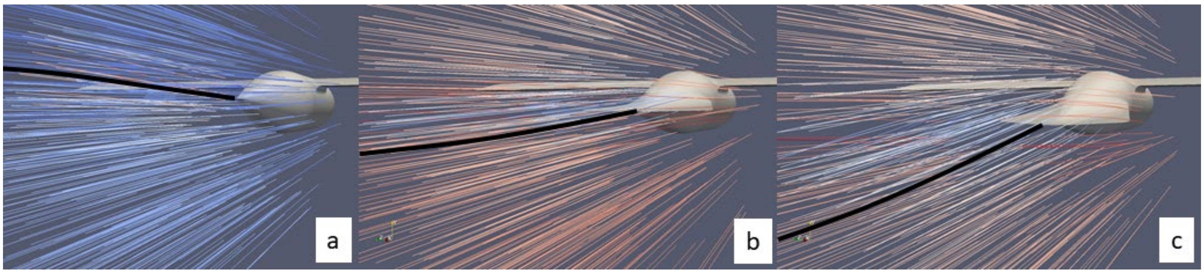

Figure 6.3 This set of pictures shows streamlines derived from the measured flow vectors using the visualisation tool, Paraview. Frame a) shows the body without a trailing edge and some upwash is visible in the wake. Frame b) and c) show progressive downward deflection of the trailing edge with increase of downwash in its wake.

6.7 Discussion

It was possible to observe the downwash deficiency resulting when a body without a trailing edge was placed on a wing. The presence of such a body causes some inboard upwash, which suggests that some adverse inboard vorticity is shed. It was also possible to demonstrate that the trailing edge would change the downwash profile and that downwash could be manipulated by the angle and the spread of the trailing edge. This could in principle then serve to provide the ideal spanwise circulation distribution during cruise or to intensify central circulation significantly as one would require it from a high lift device. Furthermore, it was possible to demonstrate that the centre of pressure moved in a stable way with changes of the angle of attack if a trailing edge was present and if the centre of gravity was suitably placed.

It may be argued that the aft body in all described experiments was fitted with a delta wing, which could be seen as just another embodiment of an empennage. If one then allows for boom and empennage optimisation, one will probably find the boom to reduce in diameter and increase in length while the delta wing will grow in span and shrink in chord to just become the typical tail wing of Pénaud. Is the described feature just another wing on a short tail boom? The delta wing idea was applied by investigators of the bird tails, for example, by Thomas [7], who modelled the avian tail as an independent delta wing. However, Evans et al. in their consideration of the role of the bird tail, warn that this approach lacks predictive reliability and should be used with caution [10]. This author adds that the body with the feature providing the trailing edge (like a blended delta plate) must be considered as a single integrated aerodynamic feature. The centre of pressure of this body is not located within the delta as it will be for a delta wing on its own. Instead, it is located further forward on the body and allows for a location of the centre of gravity practical in terms of useful lift and less sensitive in terms of pitching moments. The role of the aft body plate is then foremost to form the trailing edge to the body rather than forming a separate wing. As such, it is the lift of the entire body which is more important than the lift it produces for control.

When spread, as typical on a bird when a high lift coefficient is needed, the lateral extent is often sufficiently close to the wing trailing edge so that it rather serves as a flap element of the wing instead of acting as a separate wing in isolation. The potential to make the trailing edge feature extendable and retractable to be part of the wing high lift device seems very important and will be part of further investigations. The role of the bird tail as a high lift device or flap has been described [8, 15].

6.8 Conclusion

These tests did not have as their objective to find precise fuselage shapes or methods of trailing edge control to provide and maintain the desired spanwise circulation distribution. Such work remains to be done. However, the investigation confirmed that circulation *could* be uniquely controlled by manipulating the body trailing edge deflection and spread. This supports the speculation that birds and bats may use this strategy to their advantage. Therefore, it is expected that the controllable fuselage trailing edge is part of the ideal aircraft configuration. In cruise, it only needs to contribute to the central circulation to achieve the best span efficiency. During flight phases of lowest dynamic pressure, it may serve as a central flap to intensify the central circulation as this is where the circulation peak is most effective. During flight phases with the performance objective of minimum power, the tail feature can be employed to lower the effective wing loading. Furthermore, modification of the tail planform will change the aircraft neutral point and it can therefore be part of the static margin control system for the efficient control of balance. The trailing edge feature can also be arranged to serve in the mode of an airbrake, an opportunity which very few aircraft can directly exploit under the constraints of the current typical arrangement. The manipulation of the fuselage trailing edge can in principle also be done asymmetrically to induce lateral forces. This could be employed for lateral control or balance as is done by birds. When developing the fuselage flap for landing, the undercarriage challenges should be considered because this tail feature offers the opportunity to provide a useful contact point with the ground in the rear of the aircraft.

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Chapter 7

Features Expected in the Ideal Aircraft Configuration

7.1 Background

Chapter 5 introduced the hypothesis that the ideal aircraft would contain a combination of features and, in concept, for the typical flight objective these features would always be the same, regardless of the application within the domain under discussion. Several of these features differ from those of the current art and, in combination, should lead to solutions of superior flight efficiency. As the implementation of superior solutions is environmentally and socially desired, an enabling disclosure has been published as a patent, which appears in Appendix D. This chapter consolidates the foregoing discussions, leaning on this disclosure. In its published form, the legal language departs from the technical style of this document. This chapter summarises its content using the terminology of this thesis. The patent's figures are reproduced here so that the same reference numerals apply in all descriptions.

7.2 Features Expected in the Ideal Configuration

Essentially, the patent gives priority to the set of features (genes) that need to be combined within one design to implement the proposed ideal configuration. In the terminology of this thesis, the top-level features are those defining the family of idea aircraft configurations:

1. Its protoflyer has the gull-wing posture and it can employ static margin control.
2. Its inflated flyer has a discrete central body with a trailing edge that can be adjustable.

To elaborate, the protoflyer is essentially only a wing that has the following features:

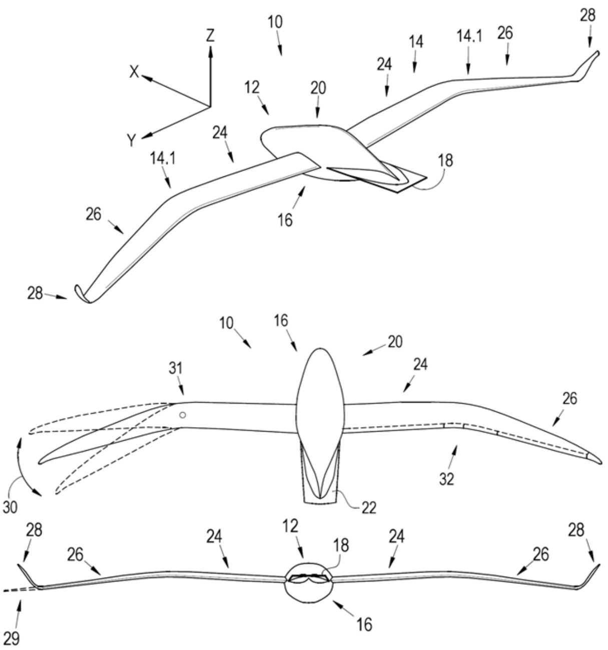
- It has polyhedral and poly-sweep, offering a posture that is longitudinally and laterally stable with a suitable dihedral effect.
- It can have active articulations for static margin control.
- It can have active weight shift for static margin control.
- It has flexible camber along the entire span of the wing for spanwise circulation control.
- It has wingtips that can be arranged in a variety of postures as an active, controllable or passive feature.

The inflated flyer has a body that has the following features:

- A fineness ratio in the order of 4.5 (between 3 and 7);
- a horizontal trailing edge,
- of which the deflection can be manipulated to control circulation and the position of the centre of pressure on the body; and
- the spread (and length) can be changed to control wing loading, circulation and the position of the centre of pressure on the body and to control the aircraft planform for static margin control.

A patent only describes the physical appearance of a feature, rather than its purpose or function. Therefore, it commits to typical embodiments as a basis for description. Here, these descriptions are summarised, but their purposes are also mentioned.

7.2.1 Gull-Wing Protoflyer

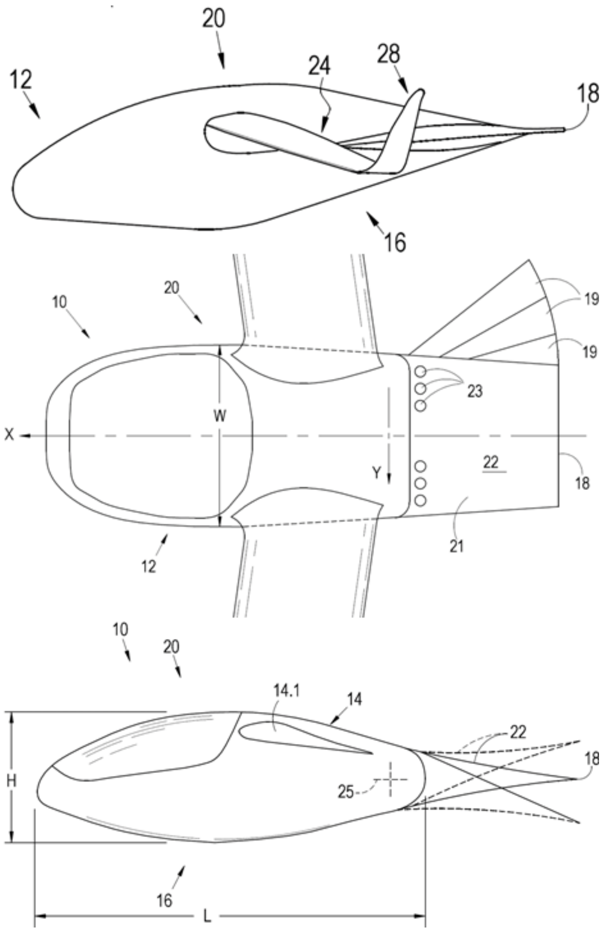


Essentially, the gull-wing protoflyer is derived from the ideal wing within a range of different postures, which it could assume if five articulations of sweep and dihedral angle were allowed along the wing. That is a central articulation, one at each wing wrist, 31, approximately at half the semi-span, and one articulation at each wingtip, 28, 29. Thereby, wing 14 is divided into a pair of inner wings, 24, a pair of outer wings, 26, and winglets, 28, (or wingtips, 29), all being described at proposed angles of sweep and dihedral. The winglets, 28, are treated as optional features, which become differentiated when in the upright posture described, otherwise, they are simply viewed as extensions, 29, of the outer wings, 26. However, it should be noted that the wingtip, 29, is described as a differentiated feature because it may play a differentiated functional role. Articulations should be viewed as design variables and not necessarily as in-flight variables of control. However, the in-flight variability is allowed for and, for some applications, is specifically encouraged at the wing wrists, 31, as part of one concept of static margin control, allowing the in-flight variation shown by 30.

The wing of such an arrangement can offer longitudinal and lateral stability, which is suitable for the combination with the body. Its size should remain close to that of the ideal wing that is minimised for its specific flight objective. The winglets, if needed for suitable directional control, can make a positive contribution to the flight efficiency, which the vertical wing of the typical current art does not do. In this posture, the structural centre of the wing is close to its centre of pressure. This implies that the structural centre and the centre of gravity of the aircraft are close together, which is advantageous in terms of structural mass.

With spanwise flexibility of the wing camber, using adjustable control surfaces along the trailing edge, 32, the spanwise circulation distribution can be adapted to remain ideal in any flight condition. Static margin control can then be used together with spanwise wing twist adjustments to obtain balance and best span efficiency simultaneously. The static margin can be controlled either by moving the centre of gravity or by changing the aircraft planform, or both.

7.2.2 Discrete Body with Adjustable Trailing Edge



The fuselage, 12, is described as tailless, thus without the tail boom and the empennage. A differentiation is made between the container for the payload, 20, and the aft body, 21, which terminates in the horizontal trailing edge, 18. The recommended range of fuselage fineness ratio is between 3 and 7, with the typical value in the order of 4.5. This range reflects the fuselage, which is specialised in favour of mass and drag in that it has the lowest fineness ratio for a given flow regime to allow pressure recovery without drag penalties from flow separation or compressibility [1]. The round body of fineness ratio = 1 (the sphere) has the best volume to surface area ratio and the lowest bending loads in its structure and therefore serves as an attractor when optimising for the structural mass and the wetted surface. However, it is unsuitable in terms of pressure drag. To minimise drag, the nose cone will be shaped to take the best advantage of laminar flow, and the aft body will offer the shortest pressure recovery region, beginning directly after the nose cone, without a section of constant cross-section. This will be the shortest tail cone for separation-free pressure recovery. In some applications, practical considerations may require some flexibility in the fineness ratio as it is expected that different family members of a specific design may include a fuselage mid-section of constant cross-section between the nose cone and the aft body, which are both common to all members of the family while the length of the constant midsection is longer in stretched members of the family.

The fuselage trailing edge feature, 18, is described as a flap, 22, adjustable in deflection angle, in spread and perhaps in length. The trailing edge is shown to have a minimum lateral extent, a retracted condition, 21, which would typically be associated with the cruise condition when the edge feature is only large enough to restore the central circulation otherwise lost due to the body disrupting the wing. This contribution allows the wing to be smaller than it otherwise has to be. In its extended or spread form, 19, it serves to reduce wing loading as is desirable, for example, for flight objectives with the performance objective of minimum power or minimum rate of sink. It will also alter the aircraft planform and thereby change the position of its neutral point and its centre of pressure.

In its extended, 19, and downward deflected arrangement, it serves to intensify central circulation as part of a high lift system of the aircraft as may be required, for example, during landing. In this condition, the central circulation over the body and the proximal portion of the wing can be significantly stronger than that of high lift devices on only the wing [2].

The fuselage trailing edge may render the fuselage as longitudinally stable. A structural advantage can be gained from the wider fuselage (given the lower fineness ratio than that of the typical current art) as the wing structure is shorter for a given span and the fuselage structure is shorter for a given volume.

The fuselage centre of pressure can be close to the wing centre of pressure. This implies that the aircraft centre of gravity and the wing and fuselage centres of pressure are close together, which is advantageous in terms of structural mass.

7.3 Summary of Advantages

This section describes the advantages that the proposed features may bring to a design when comparing it with designs of the prior art. Prior art may include the typical Pénaud arrangement or other alternatives discussed in Chapters 3 and 4. The advantages are organised under specific headings.

7.3.1 Pitch Stability

The proposed arrangement gets practical pitch stability from the wing *and* the fuselage without a boom and a secondary wing, and without requiring reflex on the aerofoils. By contributing to longitudinal stability, the fuselage can be of any relative size without requiring the wing or an empennage to provide for its stability. Thereby, the arrangement is insensitive to the inflation factor, and it offers general suitability.

7.3.2 Yaw Stability, Damping and Control

In the typical current art, yaw stability, damping and control come with a permanently exposed feature that may be unproductive for much of the mission. The proposed arrangement can achieve acceptable lateral flight mechanic properties from the wing alone. Outer wing anhedral in suitable combinations of sweep-back provides this function. In designs in which such properties need to be temporarily enhanced by vertical surfaces, these can be provided temporarily using controlled winglets, which are always productive as part of the wing. Even if permanently in the upright posture, a winglet can increase the effective span of the wing.

7.3.3 Structural Centre of the Wing

The centre of pressure of the aircraft can be viewed as having a contribution from the wing and one from the fuselage. For balanced flight, the resultant centre of pressure of the aircraft needs to coincide with its centre of gravity. This arrangement allows that the wing and the fuselage can be arranged such that their respective centres of pressure, centres of gravity and structural centres all congregate in close proximity. This offers advantages in terms of the structural mass.

7.3.4 Control of Balance and Circulation

In the typical current art, the control of balance is not deliberately isolated from the control of the circulation distribution. On the Pénaud arrangement, this is acceptable, as the control of balance has very little impact on the quality of the circulation distribution. However, on the typical single-wing aircraft, the consequence on efficiency can be unacceptable. This strategy provides specifically for separating the control of balance from the control of the spanwise circulation distribution.

7.3.5 Lower Fuselage Fineness Ratio

The aerodynamic body of a given volume, ideal in terms of drag has a fineness ratio in the order of 4.5 depending on the flow regime [1, 3], while the current art employs fineness ratios typically higher than 7. This lower fineness ratio also has positive structural implications both for the fuselage and the wing. Bending loads are smaller than those of fuselages that are longer and have to carry the same load distributed over a larger longitudinal extent. Bending reactions have the benefit of a larger cross-section. Furthermore, a wing of a given span on a wider body has lower root bending loads.

7.3.6 Body Lift

The fuselage of the typical current art is not designed to contribute to lift. Instead, it disturbs wing circulation, thereby harming the span efficiency. This arrangement provides for a fuselage that can contribute to lift. During cruise, its circulation only needs to be sufficient for best span efficiency to be attainable.

7.3.7 Fuselage Flap

It would be desirable for the central circulation to be most intense when a high lift coefficient is required. The fuselage of the typical current art rather interrupts the high lift devices on the wing instead of being part of it. This arrangement provides for a fuselage that accommodates a flap, which could cause intense circulation over the fuselage and the inner portions of the wing with the centre of pressure of such circulation close to the centre of gravity of the aircraft, so that a change in pitching moment with flap deflection can be small. This has an important implication for the size of the wing, which is designed for the maximum aircraft lift coefficient. With a large contribution to total lift from the central circulation, a smaller wing is sufficient and, for a given span, the wing bending moments are lower for the centre-loaded circulation distribution.

7.3.8 Landing Flare

A wing and a lifting body are capable of producing drag on the order of magnitude such as that of the lift. However, this requires the angle of attack to be rather high. Such high drag can be very useful during the landing phase to dissipate the last energy of flight aerodynamically. In the typical current art, the angle of attack during landing is constrained by the tail boom. Without this constraint, some implementations of this arrangement can take advantage of the landing flare, for which higher angles of attack must be reached.

7.3.9 VTOL Arrangements

Vertical take-off and landing using propulsive lift are often difficult to integrate with the efficient arrangement of a lifting wing. Tiltrotor or tilt-wing aircraft are examples of the current art in which airframe articulations are required for the transition from take-off to cruise. In this arrangement, the entire aircraft can tilt from vertical propulsive lift-based flight into the horizontal wing-based flight without any complex in-flight changes to the airframe, without the need for structural articulations.

7.3.10 Wing-in-ground-effect Aircraft

A small wingtip clearance changes the lift and drag on an aircraft, the effect exploited by wing-in-ground-effect vehicles. The arrangement of the gull-wing is suitable for small wingtip clearance, making the arrangement suitable to such wing-in-ground-effect vehicles. Given that the ground effect can be exploited during take-off and landing, this arrangement can offer good short-field properties for normal operations.

7.3.11 Wingtip Clearance

Straight swept wings of the current art sometimes have to compromise on the dihedral effect in favour of better wingtip clearance by reducing the anhedral on the wing. This may contribute to undesirable flying qualities such as the tendency to Dutch roll. This arrangement includes a portion of the wing that should have some dihedral, which then allows the uncompromised anhedral on the outer wing before tip clearance becomes a problem. The polyhedral arrangement offers more design variables to find a better compromise between wingtip clearance and the dihedral effect.

7.4 Discussion

The advantages described above, which relate to lower mass, viscous drag and better span efficiency, may all separately make only tiny contributions to improved efficiency. However, in combination, the collective improvements are significant. Ultimately, they will reflect directly in a lower carrier mass with lower total drag. If implemented in a transport aircraft, both these improvements combine to further reduce the fuel required for the mission. Thereby, the direct improvement will be substantially leveraged. Early estimates by Kruger et al. [4] put this leveraged improvement of efficiency from mass and viscous drag reductions of the fuselage alone on the order of 16% when applied to a typical airline fuselage. Considering other contributions, the leveraged improvements are expected to be on the order of 22% at the type of operation typical in the airline industry.

7.5 Closing Remarks

This disclosure describes the principles for the implementation of the features of the ideal configuration to any typical flight objective. However, it will require elaborate investments in the effort of design to derive the details by which the proposed features will suitably combine to offer the best flying qualities, as well as improved efficiency. A long road of refinement will have to be travelled before the improvements become visible. To put such investments into the perspective of the economic statement in Chapter 1, one may consider the cost of fuel unnecessarily burnt daily. For operations based on the current art, this waste of fuel was estimated at 150 000 tons per day. In principle, the resources spent on avoidable waste in future could quite rapidly accommodate the development of better alternatives if such waste could indeed be avoided in future. It will take courage to make the step-change towards such a future state.

7.6 References

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Chapter 8

Summary, Conclusions and Recommendations

Reflecting on the work presented, the key conclusions are summarised below before mentioning some recommendations for the initiative at large.

8.1 Summary

In the review of the development of the current art, reference was made to three epochs, which reflected the timescale of progress on the core questions of aircraft design. In the first and longest epoch, uncertainty prevailed whether human flight is even possible. Only the few who believed it was worked towards its achievement. Those working on the development of alternatives today face a similar uncertainty: whether solutions better than the current best even exist.

The next half a century was dedicated to establishing how best to build aircraft. Once all defining features of the current dominant configuration had been established, the second epoch came to its end in the late 1950s. Only then could refinement and optimisation receive priority in the ongoing process of incrementally advancing flight efficiency in the third and current epoch. In terms of alternatives, the second epoch is ongoing, as no alternative has yet been confirmed to be viable and superior, let alone having established how best to implement such an alternative.

With the view on the current uncertainty about the superiority of the current art against proposed alternatives, it seemed helpful to organise the aircraft design space into an imagined evolutionary family tree with the hypothetical ideal wing [1] as a common ancestor. In doing so, relationships between configurations could be recognised and various developmental strategies could be compared by their inflation factors and their impact on span efficiency.

With a focus on the principal performance objectives, it seemed that sufficient commonality exists among the majority of flight objectives, so that a single family of configurations should be ideal for the majority of objectives. This hypothesis suggests that the search for the best aircraft configuration should be a search for a single family of configurations. Rival candidates could then be compared independently at the developmental levels of the protoflyers and inflated flyers.

Comparative evaluation showed that the current dominant solution is not without avoidable deficiencies. Therefore, it did not seem to qualify as a candidate for the proposed ideal configuration. However, its status of being dominant confirmed that the notion is feasible, in that a single configuration can be suitable for the majority of flight objectives. Evaluations of the most prominent alternatives that have been claimed to be superior showed that general suitability is lacking. This is a quality that the members of the ideal family must have.

Exploring further alternatives at the first developmental step from the ideal wing to the fully stable protoflyer revealed that the ideal wing could simply assume a special posture to achieve both longitudinal and lateral stability. Through this strategy emerged a new family among the single-wing alternatives to the Pénaud protoflyer of the multi-wing family. Furthermore, with only a relatively minor modification, the inflation strategy, which is best in terms of mass and drag, could offer general suitability, which its tried alternative did not. Surprisingly, the arrangement that thereby emerged had not been adequately explored before, even though the early pioneers considered it, guided by the old solution observable in nature. These early attempts were perhaps abandoned too soon when the easier solution of Pénaud was embraced.

An assessment of this old dominant arrangement revealed it to be a qualifying candidate for the proposed family of ideal configurations. This raised the question of why it was abandoned so soon and why it did not receive further reconsideration. A review of the historic development showed that wing twisting and static margin control were discarded very early in favour of easier ways of control by wing-based control surfaces on rigid wings and airframes. This could be done quite efficiently on the Pénaud arrangement. A review of attempts at flight without the empennage revealed that, when the same approach was applied to the single-wing arrangement, the penalty for maintaining balance could be substantial.

The question then became whether balance could be maintained without much penalty on flight efficiency by the proposed protoflyer of the gull-wing configuration. Therefore, the gull-wing configuration was assessed in qualitative flight experiments to assess its flight mechanic properties and handling qualities. These experiments demonstrated that good stability and control properties can come from the wing alone. Static margin control was found to be useful to avoid the efficiency penalty of a stable layout [2] without requiring secondary wings. Such control of balance could also be performed by an unassisted pilot. Wind tunnel tests confirmed that the fuselage trailing edge could be effective to control body circulation to modify the spanwise circulation distribution [3]. A numerical investigation showed that the trailing edge could make the fuselage stable on its own.

8.2 Conclusions

- The notion of a single family of ideal configurations seems feasible and far more likely to be meaningful rather than trivial, as discussed in section 4.2.6.
- The current dominant solution does not appear to qualify as a candidate for the ideal family as it involves deficiencies that are, in principle, avoidable, as discussed in section 4.3. Thus, this work supports the widely held notion that better flight efficiency may be achievable by another configuration.

- Other evaluated alternatives lack the quality of general suitability, which the ideal configuration must have, as discussed in section 4.3.
- The candidate that appears to qualify (the gull-wing configuration) is already a well-established dominant configuration within the same domain, as discussed in section 4.4.
- Preliminary experimental evaluations have revealed no compelling reasons thus far to rule out the gull-wing configuration and its method of control for use in aviation. The experiments and numerical evaluations described in chapters 5 and 6 indicate that it could satisfy the basic requirements typical in aviation. It appeared to be suitable for the majority of flight objectives and it is expected to offer superior efficiency as discussed in 4.4.
- Wind tunnel experiments confirmed that a fuselage trailing edge could be employed to control circulation over the body, as described in Chapter 6.

In conclusion, the search for alternatives should be continued, but it is proposed that only candidates offering general suitability need to be considered. Therefore, the gull-wing configuration should be seriously considered for any new aircraft design.

8.3 Recommendations

8.3.1 Core Assumptions

The arguments presented in Chapter 4 rest on some critical assumptions. It is recommended that some of these ought to be tested further.

It is assumed that flight requires a wing and that the wing of minimum drag is that described by Prandtl and Munk: a single straight wing with a high aspect ratio. While the argument mentions only the ideal lift distribution without being specific about which distribution is ideal, the ideal wing itself, in its equation for volume uses the elliptical distribution as if it is ideal. If it turns out that some combination of stagger of wings could offer better efficiency, the ideal wing proposed here loses its status as a common ancestor to the family of ideal configurations, and the outcome of this work may be quite different.

Another important assumption is that relating to propulsion. It has been assumed that a propulsion system can be imposed upon a basic configuration or integrated into it by adding it externally, by integrating it internally, or by making it retractable or detachable. If the basic configuration of an unpowered optimum design is fundamentally different from its optimum powered counterpart, one would need to jump from one ideal configuration to another, which would render the hypothesis of a single ideal family refuted. It is recommended that proposals of alternative propulsion systems be tested against this concern.

8.3.2 Outlook

Further work should consider how the configuration can be developed for economically significant implementation in the airline industry. It is unlikely that this sector will lead the step-change into unfamiliar terrain. The unavoidable entrenchment evident in the industry as expertise and experience developed over more than half a century of continuous refinement will conserve the preference for the current art. Beginning again at the configuration level will inevitably bring along new tragedies and disappointments, which the pioneers previously had to endure and overcome. To catch up on more than half a century of refinement will require several generations of the new art. Initially, it will fail to demonstrate superiority and will appear to confirm the sceptics, who will insist upon remaining with the current art. Without convincing demonstrations of superiority, the proposed configuration has little chance of being seriously considered. No number of theoretical studies can substitute actual demonstration. Demonstration will thus be the key objective of the next big step.

Flight efficiency, in itself, is not easy to demonstrate and is never the single decisive quality. Safety will always remain the obvious highest priority, and any design must offer good all-round qualities in all aspects of the system. In this context, flight competitions among aircraft modellers and in the sport of gliding offer a unique stage for comparison in competition. Free-flight models and radio-controlled models can help establish the details of the protoflyer and help confirm if a superior protoflyer does, indeed, exist.

Currently, the sailplane and the airliner, as examples of inflated flyers, are based on the same configuration and thus the same inflation strategy. If the hypothesis of the family of ideal configurations is meaningful and a better configuration exists, the same configuration should again be best for both. Thus, it is proposed to endeavour to first develop a family of sailplanes that should eventually win gliding competitions. One has to generously allow for several early designs to resolve the remaining fundamental issues without demanding success in competition of the early designs. Early development will have to focus on issues of flight safety beyond all the edges of the envelope. Tucking, spin recovery and flutter are some of the topics that need careful assessment at all stages of development. The details of fuselage trailing edge adjustments and deployment into the high lift mode need to find good technical solutions. Details for implementing twisting of the wing trailing edge need to be developed. Simple aspects such as pilot placement and field of view also require new thinking and experimentation. Undercarriage coupling is expected to present new challenges, and water ballast will be more challenging to accommodate and manage in a glider wing of the proposed arrangement.

While these challenges may seem daunting, the opportunities should bring a sense of excitement to the developers. The airframe can be significantly lighter to allow a larger range of wing loading within the mass limit of a class. A smaller wing will stretch high-speed efficiency to a new level. The opportunity of an elaborate central flap providing lift over the fuselage will also give smaller sink rates and turn radii to expand the scope of flyable territories and weather conditions. Airbrakes no longer need to extend from the wing and the landing can exploit a larger angle of attack in a flared landing. Together with a lower landing weight, the landing off the field becomes less problematic. The fuselage offers the opportunity to implement an occupant support arrangement for better protection [4]. Electric propulsion can take advantage of a lower take-off mass to offer more practical self-launching gliders. The hangar and the transportation trailer can be much smaller, and the wing and fuselage parts can be carried by one person when assembling or disassembling the glider.

Provided that all issues of flight safety can be reliably resolved and that good all-round handling qualities can be provided, winning still needs to be achieved. If winning becomes a regular occurrence, the top pilots will have to take the dreaded step to change to the new configuration. In time, others will want to follow. When this starts to happen, the long road of refinement of the new configuration can comfortably proceed to mature the new technology. With time, new expertise and experience will show the pitfalls and opportunities, and the new approach to aircraft design will spill from research into the teaching tracts of aeronautical engineering. Many existing aviation records will have to be challenged once more, and human-powered flight will demonstrate new achievements. Every field in aviation will begin to take notice and may apply the new approach, and sooner or later, the airline industry will follow.

The prospect described above may seem unlikely, yet it seems more likely than that which the blended wing body or other alternatives would have to face. Alternatives that are not suitable for the sport of gliding, like the blended wing body or other inflated wing alternatives, would have to enter directly into the field of larger transport planes. All-round experience will then not have the opportunity to mature in more flexible sectors of aviation.

In his book on sailplane design, Fred Thomas [5, 6] describes, in the closing remarks, a tentative vision of the sailplane of the future. His description in the original German version of this book allows the main elements of the gull-wing configuration to be imagined. Thereby he allows the idea that alternatives may in future still change the mature configuration of the sailplane. The sport of gliding has often served to test ideas in aviation [5]. It could perhaps do so again for the ideas presented in this thesis.

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On the wing density and the inflation factor of aircraft

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ABSTRACT

The aviation industry is dominated by the domain of heavier-than-air, fixed-wing, subsonic flight, and central to any design in this domain is the wing itself. One of the earliest debates in aviation still centres around the usefulness of the wing volume. On the one hand it is held that the wing, as an inevitable necessity, should provide the volume also for the payload. On the other, it is argued that more efficient wings do not even have sufficient volume for the entire wing structure. This work proposes precise definitions of the *Wing Density* and the *Inflation Factor,* two parameters that can quantitatively reflect the economic and technological trends in aviation. The wing volume of a hypothetical *Ideal Wing* is derived from the *Operational Parameters* of any given *Flight Objective* and compared to the volume requirement of that flight objective. We conclude that the dominant aircraft configuration of the future is likely to remain within the same family of the current dominant configuration, in conflict with some older predictions.

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NOMENCLATURE

A_{AF}	cross section area of an aerofoil, m^2
AR	aspect ratio
b	wing span, m
c	mean wing chord, m
c_R, c_T	root and tip chord of a wing respectively, m
c_d	coefficient of profile drag of an aerofoil based on c
C_D	coefficient of drag of the entire aircraft based on S
c_l	coefficient of lift of an aerofoil based on c
C_L	coefficient of lift of the entire aircraft based on S
D	total drag, N
e	span efficiency factor
f_{AF}	aerofoil area fraction, fraction an aerofoil occupies within a rectangular envelope
f_{PT}	planform transformation factor, transforming the wing box planform
f_{PTE}	factor to transform the wing box to an elliptical planform
f_{PTT}	factor to transform the wing box to a tapered planform
g	gravitational acceleration, taken as 9.81 m/s^2
IF	inflation factor
L	aircraft lift, N
m	aircraft mass, kg
Ma	Mach number
n	manoeuvring load factor
Re	Reynolds number
S	wing planform area, used as reference area for coefficients, m^2
t	relative aerofoil thickness as % of chord, c
V	true air speed of flight, m/s
Vol_{AC}	total volume of an aircraft, enclosed by its wetted surface, m^3
Vol_{IW}	volume of the ideal wing, enclosed by its wetted surface, m^3
Vol_{WB}	volume of the wing box, m^3
Vol_{Wing}	volume of a wing, m^3
Z	taper ratio
ρ	air density at flight altitude, kg/m^3
ρ_{AC}	mean density of an aircraft, kg/m^3
ρ_{IW}	mean density of the ideal wing, kg/m^3
ρ_{Wing}	mean density of a wing based on aircraft mass and wing volume, kg/m^3
μ	the dynamic viscosity, kg/ms
ν	the kinematic viscosity, m^2/s

1.0 HISTORICAL CONTEXT

In 1904, as powered aviation got off the ground, Ludwig Prandtl introduced the notion of the boundary layer and offered explanations for the phenomenon of viscous drag[(1)]. With power plants of marginal power densities, early aircraft required low wing loading to find their power match. External bracings and biplane configurations offered successful structural solutions for the fledgling domain of heavier-than-air aviation. With better comprehension of drag, it was soon recognised that thicker wings could offer useful volume with little penalty in aerofoil drag. The structures of unbraced wings could hide within this volume. Though heavier, and penalised by induced drag, its lower parasitic drag allowed for faster flight. As the understanding of inviscid drag consolidated through the work of Lanchester and Prandtl, the trade-off between viscous and inviscid drag became the topic of perhaps the most persistent debate in aviation.

Hugo Junkers committed to the opportunity of useful wing volume in the year before Prandtl's landmark clarification of induced drag in 1911 when he sealed this conviction into his 'Volume Patent' in 1910(2,3). He therein suggested that not just the wing structure but also the engines, their fuel, the crew and the payload should eventually reside inside the wing. He thus hinted that the *Flying Wing* could be the aircraft configuration of the future. The Junkers *G 38* airliner began to enact this idea into service in the decade leading to the Second World War. In 1930 Junkers incorporated the idea fully into the design of a 100-ton flying wing intended (but never built) for transatlantic air travel(3).

The internal wing structure is part of the solution that has by now dominated aircraft design for almost a century. Though fuel or ballast also commonly reside inside the wing, the fuselage has never disappeared entirely into it, and engines seldom have. From early on, a dedicated fuselage holding tail wings (the empennage) formed part of a robust solution to the challenges of stability and control. Although the Horton brothers and many others demonstrated long ago that such tail wings can be considered redundant(3,4), they remain part of the dominant solution today, together with the rather long and slender fuselage that holds them.

Proponents for alternatives to the current dominant aircraft configuration cast serious doubt on its supremacy by claims that superior solutions exist in terms of flight efficiency(5-7). Much research is motivated by this speculation(8). It also remains common practice in aircraft design to dedicate substantial efforts to the choice of the configuration(9-11) despite the existence of the well-established dominant solution. If the aircraft configuration space were divided into only two broad families, one could follow Stinton's(12) classification of aeroplanes into a *classical family* and an *integrated family*. The classical arrangement has distinguishable lifting and non-lifting parts as in the current dominant configuration, often called the 'tube-and-wings' configuration. The integrated family is characterised by the attempt to avoid exposure of any non-lifting aircraft surfaces to the air, and the Volume Patent is thus at the core of such arrangements. The continuing debate should at least attempt to answer to which family the aircraft of the future will belong.

Nickel and Wohlfahrt(4) offer an example to dismiss the pure flying wing as a solution to the flight objective of a well-known large transport aircraft. They demonstrate that the volume requirement of this specific flight objective cannot be practically met by a pure flying wing and conclude that a commercially viable all-wing airliner seems unfeasible with the technology of the time. However, it is not clear from such an isolated example how sensitive this conclusion might be to changes in the flight objective parameters, or to what extent a useful integrated arrangement would deviate from the pure flying wing.

Torenbeek(9,13) explores the matter of volume requirement more broadly by investigating variations of the ratio of fuselage volume to wing volume by also allowing two operational parameters (cruise speed and density) to vary. Thus, the variation from the classical arrangement towards the integrated arrangement is considered as the fuselage relinquishes an increasing amount of its volume to the wing. A variety of integrated arrangements were compared against an existing large conventional baseline without a conclusive statement.

In Torenbeek's analysis[9,13], no special consideration is given to the payload grain size, which is part of a practical volume requirement. Also, that work was performed in the context of the large transport aircraft, the only significant domain in which the integrated arrangement is seriously considered as an attractive proposition for high-altitude cruise at perhaps reduced speed.

Proposals by Burnelli in the early 1920s to shape a dedicated fuselage as a lifting body have also not found sustained implementation[14]. However, in recent decades such concepts have been reconsidered in many different variants with many different blended-wing bodies (BWBs) studied in the USA, initiatives like the *VELA* in Europe and *TsAGIs* integrated wing body, lifting body, and flying wing in Russia, as summarised by Lowther[15].

As a contrasting alternative it is proposed that wings should be thinner and of higher aspect ratio. Such wings would also require less sweep but would need external bracings[6,7]. These braced wings then have particularly little volume and thus inevitably belong to the classical family of dedicated wing and body.

The above gives a superficial overview of the debate surrounding wing volume, which is a core configuration issue. Mason observes that 'a simple, easy-to-understand analysis' to gauge when wing volume can and cannot be useful is still missing[16,9]. In response, a simple and general notion is here introduced, with two new parameters, the *Wing Density* and the *Inflation Factor*.

2.0 THE FLIGHT OBJECTIVE, THE IDEAL WING, WING DENSITY AND THE INFLATION FACTOR

In order to formulate a hypothetical ideal to serve as an evaluation reference, it is necessary to consider the physical limitations of aerodynamics independent of operational compromises and limitations. The notion of the *Ideal Wing* is here used as such a baseline. Any real aircraft design inevitably must offer a compromise suitable for a large variation in objectives. To avoid the need to compromise, one must derive a unique objective from the large scope of variation. The notion of the *Flight Objective* is here used to give focus to a specific objective. It is then possible to derive a unique ideal wing for any given flight objective. Its mass and volume then define the ideal *Wing Density*. Relating this wing density to the average aircraft density of a corresponding real solution yields the *Inflation Factor*. This factor serves as a measure of discrepancy between a practical solution and its aerodynamically possible ideal.

2.1 About the flight objective

Each aircraft is designed for a *family of missions*. Every flight represents a *specific mission*. Each mission is composed of a sequence of *mission segments* (Fig. 1), each segment having one specific performance objective. This performance objective, together with the operational parameters, define the *Flight Objective* of the segment.

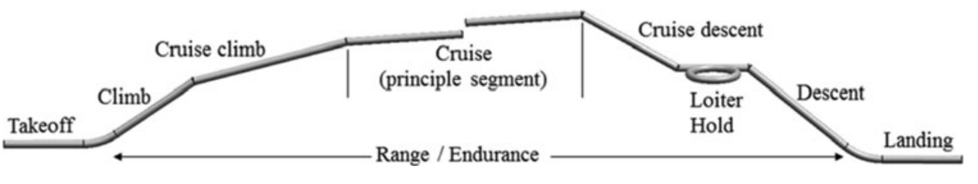

Figure 1. Any mission is a sequence of mission segments, each having a specific performance objective.

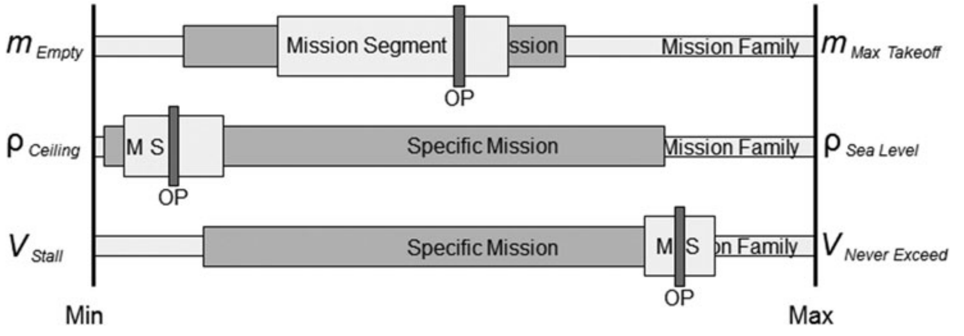

Figure 2. The Operational Parameters (OP) are narrowed down from the overall scope of variation of the Mission Family first by the Specific Mission and further by the Mission Segment (MS) to give focus to the operational parameters for a given flight objective.

The mission family defines the overall scope of *Operational Parameters* of aircraft mass m, the load factor n, air density ρ and the flight speed V, and all the *Performance Objectives* relating for example to range, endurance or rate of climb. Each specific mission narrows down the scope of operational parameters while all the performance objectives may still be of relevance. Each mission segment further narrows down the variation of operational parameters (as illustrated in Fig. 2) and now only one specific performance objective is relevant. The performance objective and the operational parameters are now specific, and an aircraft specialised for only one such specific flight objective can be without compromise. Such a hypothetical aircraft forms the basis of the ideal wing described here.

Besides the operational parameters and the performance objective, the flight objective is also concerned with other requirements. The volume requirement and the demands concerning stability and control may be applicable to all segments. Other special requirements like cabin pressure or radar signature may be associated only with some segments. Such additional requirements are then ignored since, by the definition of the ideal wing, only the operational parameters and the performance objectives are of interest.

It is normally the objective to perform any mission with the best overall flight economy and this therefore also applies to each mission segment. Overall mission optimisation and operational constraints will of course influence the choice of the operational parameters but it is here unimportant how these parameters have been chosen. The flight objective may now be defined as:

the objective to operate the aircraft at the parameters of choice (m, n, ρ and V) at the best flight economy for the given performance objective.

2.2 The ideal wing

Presuming that the physics of flight require a dynamic interaction between the flight body and its surrounding viscous medium to provide the lifting force for heavier-than-air flight, such a lifting device is taken to be a wing (a fixed wing, given the domain under consideration). A wing is then an inevitable necessity and it would be best if the aircraft needed nothing else. By ignoring the requirements for volume, stability and control, and other special requirements of the flight objective, the aircraft can be reduced to the *Ideal Wing*. Thus:

the Ideal Wing is the hypothetical aircraft which offers the best aerodynamic efficiency for a given flight objective by containing the entire aircraft in only a wing of ideal aerodynamic shape and size.

Each flight objective defines a unique ideal wing and this is without compromise, as the flight objective is specific. It serves as a reference to compare practical solutions for a given flight objective with the hypothetical ideal.

2.2.1 The shape of the ideal wing

'Ideal' in the present context relates only to the physics of lift and drag, and thus considers only the transfer of energy from the flight body to the surrounding medium while changing its momentum to provide the required lift. Thus, the ideal wing is shaped and sized to provide the required lifting force in a way that would shed the least amount of energy to the wake to achieve the desired flight objective. In terms of the induced drag, all ideal wings will therefore operate with the best span efficiency, $e = 1$. To keep the model of the ideal wing simple, the classical approximation of the elliptical planform without twist is adopted here, and nonplanar or multi-component wings are not considered.

It is the purpose of the ideal wing to serve as a baseline for size comparisons only, and by the definition offered here, issues of stability and control and of compressibility are ignored, together with the volume- and other requirements. Thus, sweep and dihedral features are neglected, but without implying that the ideal wing is necessarily without such features. The size parameters of interest for the ideal wing are insensitive to these neglected geometric characteristics. Furthermore, these size parameters are not needed with any great accuracy and therefore some simplifying assumptions are permitted to arrive at consistent parametric estimates.

The detail of the shape of the ideal wing can be debated[17,18]. However the proposed representation needs to be seen not as the confirmed actual 'ideal', but rather as a reasonable geometric representation for a comparative baseline. The baseline properties of interest are the wing volume, Vol_{IW}, its maximum thickness, tc_R, and later (not discussed here) its wetted surface. These parameters need not be known with great accuracy, as long as they are uniquely defined in terms of the operational parameters.

2.2.2 The mass of the ideal wing

As a comparative reference, the mass of its corresponding real aircraft within the mission segment under consideration is used for the ideal wing. For existing designs, this mass (and its variation during the segment) is known. Otherwise, if only payload mass is known, it is common practice to derive estimates from existing designs with similar objectives. The mass may be considered as if distributed ideally along the span such that no consideration needs to be given to the structure of the ideal wing.

2.2.3 The aerofoil of the ideal wing

The three-dimensional consequences of wing geometry can quite reliably be derived from the results of classical wing theory, given the geometric simplicity and rather high AR of the ideal wing. However, this requires information on the local circulation strength along the span as produced by the aerofoils and reflected by the operational coefficients of lift c_l and the corresponding profile drag c_d. The physical limitations of these parameters depend on the quality of the aerofoil, which affects the viscous interactions within the boundary layer.

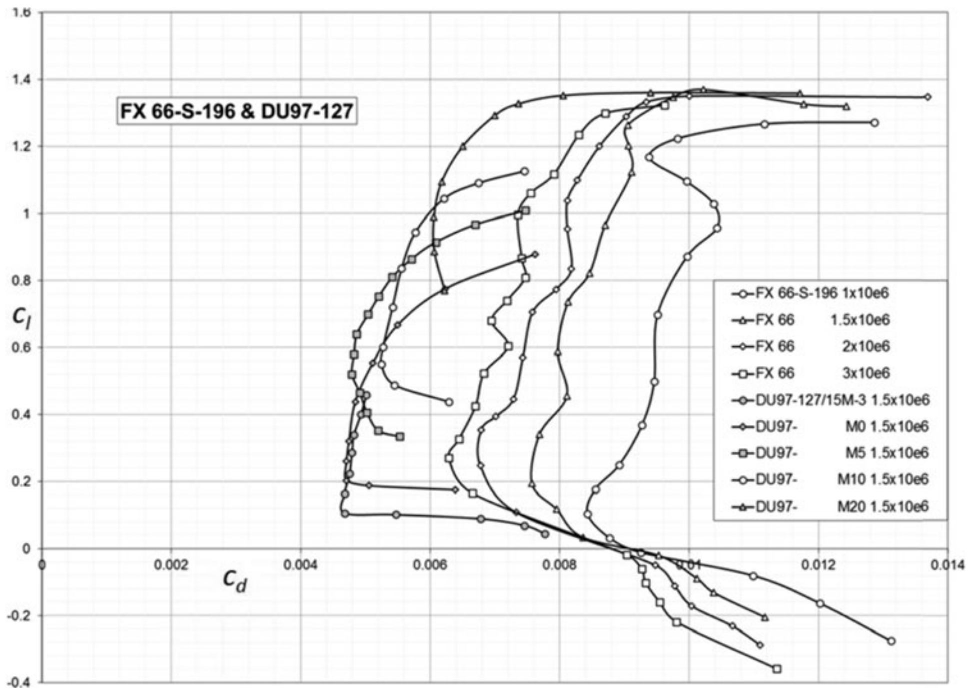

Figure 3. Experimental data of the Wortmann FX 66 aerofoil[22] at different Reynolds numbers and the Delft DU97 aerofoil[19] at different flap settings. For each polar curve, only the laminar 'drag bucket' is shown.

While the notion of the ideal wing can be applied to any mission segment, the focus is here on segments in which the greatest efficiency is desired. That excludes operations involving deliberate flow separation and implies that the best advantage is taken of laminar flow. In terms of maximum aerofoil efficiency, only one effective angle of attack is then of interest for such mission segments – that at which the wing C_L/C_D is the highest. Then, also a high maximum aerofoil c_l/c_d is of interest and the design C_L may then typically be rather close to the c_l for $(c_l/c_d)_{\max}$. Best aerofoil efficiency is usually associated with a large amount of laminar flow, and this reduces rather abruptly beyond a critical lift coefficient[19-22]. Thus, the aerofoil of the ideal wing is considered (where suitable) to be a laminar aerofoil.

Historically, one can observe a trend of improvement of the best aerofoil c_l/c_d even after the prominent jump linked to the emergence of laminar flow aerofoils during the Second World War. Fig. 3 shows properties of an early laminar flow aerofoil against those of a more recent one. One example clearly shows the influence of Re. The other shows how a flap can be used to compose a useful range of c_l for low drag operation.

For a true 'ideal' reference, the physical limit towards which this trend is converging should be applied to the ideal wing. As long as this physical limit may be unknown, realistic values for c_l and c_d of the current best aerofoils at the given operational Reynolds (Re) and Mach (Ma) numbers should be used, assuming that these are not far off this physical limit.

Any form of active boundary layer control reliant on external energy would form part of a propulsion system and is therefore not considered in this definition of the ideal wing. However, boundary layer control continues the trend of improving best aerofoil c_l/c_d and therefore needs to be considered in the wing volume debate. The corresponding augmented ideal wing offers even less wing volume.

2.2.4 The size of the ideal wing

Given the assumption of constant downwash (as implied by $e = 1$) and the rather high AR of the ideal wing, the operational lift coefficient of the entire wing, C_L, is approximately the same as the constant local coefficients of its aerofoils, c_l. Then the size of the ideal wing follows directly from the operational parameters m, ρ and V and from the aerofoil operational lift coefficient c_l. The flight speed would typically be that for minimum total drag (where the total drag is the sum of profile and induced drag only). Since there are important mission segments associated with curved flight, it is necessary to include the load factor n so that

$$S = \frac{2mgn}{\rho V^2 C_L} \qquad \ldots (1)$$

Once the AR or wing span b is known, the root chord of the elliptical wing can be derived from the mean chord c by $c_R = 4/\pi c$, with the maximum thickness of the wing then being $c_R t$. This parameter reflects the upper vertical limit within the useful volume of the ideal wing.

To compensate for variations in the operational parameters as fuel is consumed and air density changes with altitude, the flight speed could in principle be changed so that $mn/\rho V^2$ remains constant. To operate at a constant speed, the rate of climb should be balanced with the fuel consumption such that the displacement volume mn/ρ remains constant. Either way, the aircraft would operate at the best C_L throughout the mission segment for a fixed wing area. Thus, the flight objective can in principle define a unique ideal wing of fixed size despite large parameter variations during the mission segment. This approach deliberately neglects practical limitations of operation in controlled airspace to remain consistent with the underlying laws of physics rather than with artificial rules and procedures.

2.2.5 The aspect ratio of the ideal wing

The wing of infinite span (and thus AR) represents the hypothetical case without induced drag. Any real wing must have a finite AR, but which AR would be ideal for the ideal wing? Since the flight objective defines the flight speed and altitude of choice (and thus the viscosity, density and Ma), the wing area follows directly from any choice of lift coefficient as shown by Equation (1).

Now, since:

$$\mathrm{Re} = \frac{Vc}{\nu} \qquad \ldots (2)$$

where $\nu = \mu/\rho$, then, given the relationship between the chord, c, area, S and aspect ratio, AR,

$$c = \sqrt{\frac{S}{AR}} \qquad \ldots (3)$$

from Equations (1) and (2) we may write:

$$\mathrm{Re} = \sqrt{\frac{2mgn}{\mu\nu C_L AR}} \qquad \ldots (4)$$

and hence:

$$AR = \frac{2mgn}{\mu\nu C_L \mathrm{Re}^2} \qquad \ldots (5)$$

The product of dynamic and kinematic viscosity, $\mu\nu$, has units of force and increases with altitude. Recalling the approximation $C_L \cong c_l$, then an estimate of c_d can be made from measured or computed drag polars. In particular, numerical codes such as XFOIL/XFLR5 can be used to generate a series of polars for varying c_l, at given Re and Ma, and Equation (5) may then be used to compute AR. The total drag is the sum of profile and induced components:

$$C_D = c_d + \frac{C_L^2}{eAR\pi} \qquad \ldots (6)$$

and so the dimensionless drag to lift ratio is:

$$\frac{D}{L} = \frac{C_D}{C_L} \cong \frac{c_d}{c_l} + \frac{C_L}{eAR\pi} \qquad \ldots (7)$$

C_D/C_L can now be shown as a surface over the variables C_L and AR, as in Fig. 4 for one example case. Here the aerofoil is based on the DU97-127 on an imagined sailplane of $m = 600$ kg, at a density altitude of $\rho = 1$ kg/m^3. Such surfaces would ideally be compiled from properties of aerofoils specialised for any given C_L and Re at a given Ma, and a unique set of surfaces could in principle be derived by a rigorous process of aerofoil optimisation for the single objective of minimising aerofoil drag in their design points. The minimum point on such a surface would then define the ideal lift coefficient and AR for a given flight objective.

This optimisation exercise is not part of this work and the surface of Fig. 4 is offered as an example, numerically derived from only a single base geometry. No attempt at aerofoil specialisation has been made for this example other than including two flap settings. The surface does not reflect operational relationships but design relationships. A large C_L implies a small wing. It can be seen that the design landscape allows a large variation of C_L for a given AR without much change in the performance. The region around the optimum is a rather weak function of C_L and AR and the optimum is found at rather high values of C_L and AR (on the order of $C_L = 1$ and AR beyond 100 in this example). This example is used to show how such surfaces may be constructed so as to offer a baseline for the notion of the ideal wing.

2.3 Wing density

Wing density may be added to the list of useful parameters such as wing loading or span loading that characterise an aircraft. Although the absolute wing volume is of interest, a more generalised parameter results from normalising the volume with the aircraft mass to either

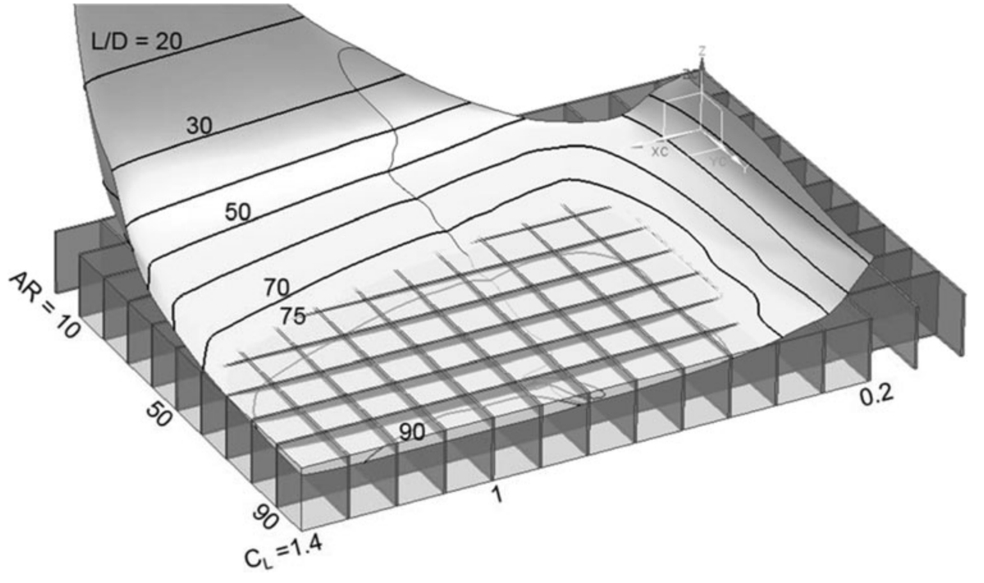

Figure 4. The surface of *D*/*L* as a function of *AR* and C_L shows, by means of the *L*/*D* contours, how C_L and *AR* should increase to get to the best performance (with the lowest region offering the best *L*/*D*). The fissure in the otherwise smooth surface separates two different flap settings.

become the specific volume (m^3/kg) or a density (kg/m^3). The latter form has been chosen here as it compares more easily with the densities of fuel and ballast. Wing density is then simply the aircraft mass m over its wing volume Vol_{Wing}:

$$\rho_{Wing} = \frac{m}{Vol_{Wing}} \qquad \ldots (8)$$

This represents the mean density of the aircraft as if it were compressed into its wing. Comparing it with the actual mean aircraft density:

$$\rho_{AC} = \frac{m}{Vol_{AC}} \qquad \ldots (9)$$

where Vol_{AC} is the *total* volume of the aircraft, one obtains a generic parameter to gauge the usefulness of the wing volume.

2.3.1 The wing volume

The wing volume can be approximated from the primary wing geometry parameters, S and AR or span b, the planform, and the aerofoil geometry. The *Wing Box* is here presented as the scalable volume, Vol_{WB}, which is later expressed in terms of the operational parameters. This box is then transformed to account for the actual planform of the wing by means of the *Planform Transformation*, f_{PT}. The wing occupies only a fraction of the wing box proportional to the *Aerofoil Area Fraction*, f_{AF}, and the relative aerofoil thickness t so that:

$$Vol_{Wing} = f_{PT} f_{AF} t Vol_{WB} \qquad \ldots (10)$$

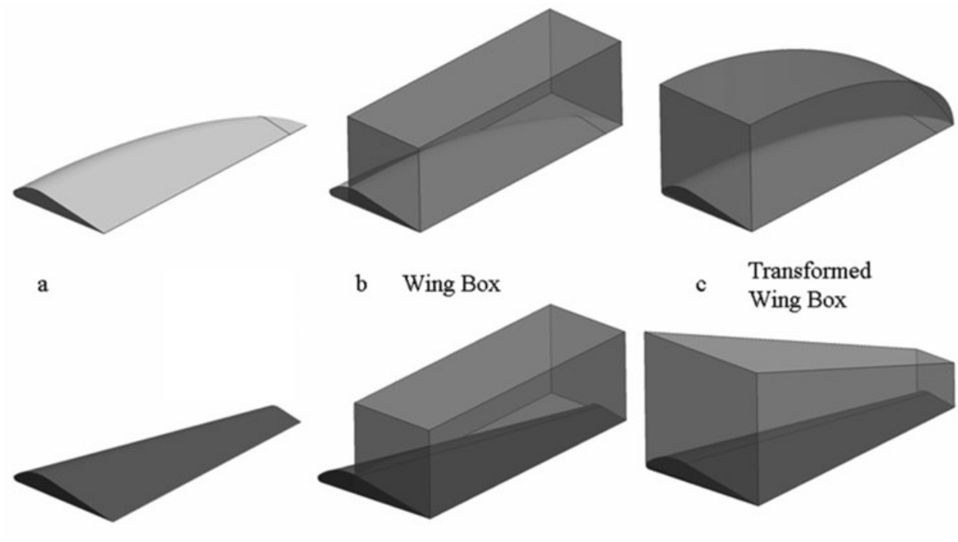

Figure 5. Wing box transformations to estimate the volume of an elliptical and a tapered wing.

Equation (10) shows how the wing box volume can be scaled to any specific, real geometry through transformations f_{PT}, f_{AF} and t to allow quantitative statements to be made on wing volume and density by simply considering the wing box volume. Illustrations of the scaling transformations are given in Fig. 5 for an elliptic and a tapered wing.

2.3.2 The wing box

The wing box can be viewed as a rectangular box having the same base area S as the wing and having a square longitudinal cross section. It is the rectangular box in Fig. 5(b) of span b with a square cross section c^2 (with c the mean chord of the wing), such that its volume:

$$Vol_{WB} = bc^2 \qquad \ldots(11)$$

The wing box volume can also be expressed in various ways, using $S = bc$ and $AR = b/c = b^2/S$, so that:

$$Vol_{WB} = Sc = \frac{S^2}{b} = \frac{b^3}{AR^2} = \frac{Sb}{AR} = \sqrt{\frac{S^3}{AR}} \qquad \ldots(12)$$

The last expression illustrates best how an increase in AR reduces the wing volume for a given wing area. The next step is to make the specific transformations of this generic shape for particular geometries.

2.3.3 The planform transformation, f_{PT}

The dimensionless factor, f_{PT}, transforms the wing box to have the same planform as the wing. The transformed wing box retains the square longitudinal cross sections, but the chord varies

Figure 6. An aerofoil comparable to the DU97 of thickness $t = 12.7\%$ has an area fraction $f_{AF} = 68.4\%$.

with spanwise location, $c = c(y)$. For a wing with single taper, the *Planform Transformation (Taper), f_{PTT}*, is:

$$f_{PTT} = \frac{4\left(1 - Z^3\right)}{3(1+Z)^2\,(1-Z)} \qquad \ldots (13)$$

with the taper ratio $Z = \frac{c_{Tip}}{c_{Root}}$. This expression, derived in Appendix A1, is undefined for a rectangular wing ($Z = 1$), but for such a wing, no transformation is needed (or $f_{PT} = 1$). The maximum taper transformation adds 33% ($f_{PTT} = 4/3$) to the volume of a wing when the taper ratio is at its minimum of 0, while a taper ratio of 0.5 adds only 3.7% when compared with the rectangular wing of the same wing area.

The *Planform Transformation (Elliptical), f_{PTE},* transforms the wing box into a volume with an elliptical planform and locally square longitudinal cross sections. For an elliptical wing of mean chord *c,* the wing root chord $c_R = 4/\pi c = 1.27c$. As derived in Appendix A2, the elliptic transformation inflates the wing box by:

$$f_{PTE} = \frac{32}{3\pi^2} = 1.08 \qquad \ldots (14)$$

This means that the elliptical wing has a 27% larger root chord and is 27% thicker at the root than its rectangular equivalent of the same wing area, and it also has 8% more volume. This is about the same as the volume of a comparable tapered wing with $Z = 1/3$.

2.3.4 The aerofoil area fraction, f_{AF}

The cross-sectional area A_{AF} of an aerofoil is proportional to its chord length c and thickness ct (with relative thickness t expressed as a fraction of c). It also depends on the aerofoil geometry for which the *Area Fraction* is illustrated in Fig. 6, and defined as:

$$f_{AF} = \frac{A_{AF}}{c^2 t} \qquad \ldots (15)$$

The aerofoil area fraction based on the square cross section of the wing box, c^2, is then:

$$f_{AF}t = \frac{A_{AF}}{c^2} \qquad \ldots (16)$$

which would also be the volume fraction of a rectangular wing in its wing box, which is typically on the order of 10%.

2.3.5 *The ideal wing density*

From Equations (10) and (12), a general geometric expression for the wing volume is:

$$Vol_{Wing} = f_{PT} f_{AF} t \sqrt{\frac{S^3}{AR}} \qquad \ldots(17)$$

Substituting Equation (1) for S here introduces the operational parameters of choice together with the proposed lift coefficient and AR, so that:

$$Vol_{Wing} = f_{PT} f_{AF} t \sqrt{\left(\frac{2mgn}{\rho V^2 C_L}\right)^3 \frac{1}{AR}} \qquad \ldots(18)$$

As a reference, the density of the ideal wing gives the highest wing (or aircraft) density for a given flight objective. Inserting the above into Equation (8) and using the elliptical planform transformation f_{PTE} gives the ideal wing density as

$$\rho_{IW} = \frac{V^3}{f_{PTE} f_{AF} t} \sqrt{\left(\frac{\rho C_L}{2gn}\right)^3 \frac{AR}{m}} \qquad \ldots(19)$$

This can be rearranged into a parameter relating to the design choice $\sqrt{C_L^3 AR}$, a parameter relating to the wing and aerofoil geometry $1/f_{PTE} f_{AF} t$ (in which $f_{PTE} = 1.08$) and an operations related parameter $V^3 \sqrt{(\rho/2gn)^3 1/m}$, and so expressed, with the constants combined into $K = 0.0106$ as:

$$\rho_{IW} = K \frac{\sqrt{C_L^3 AR}}{f_{AF} t} V^3 \sqrt{\left(\frac{\rho}{n}\right)^3 \frac{1}{m}} \qquad \ldots(20)$$

2.4 The inflation factor

With the ideal wing representing the smallest and most efficient wing capable of meeting the flight objective regardless of the volume requirement, the additional volume needed for any real solution can be quantified by means of the *Inflation Factor*. This is defined as the ratio of the total aircraft volume to the volume of its corresponding ideal wing for the given flight objective:

$$IF = \frac{Vol_{AC}}{Vol_{IW}} \qquad \ldots(21)$$

Since m of the hypothetical ideal wing has been chosen to be the same as that of the aircraft at the time for which it has been derived, the inflation factor can also be expressed as the density ratio:

$$IF = \frac{\rho_{IW}}{\rho_{AC}} \quad \ldots (22)$$

Thus, for any existing or planned aircraft design, an inflation factor can be associated with any given flight objective.

> *If one imagines that the entire aircraft could be compressed into its ideal wing, then it would have to inflate by the inflation factor before its volume would be sufficient for the required original payload density and grain size.*

Any aircraft design, existing or planned, implicitly has a unique inflation factor for a given flight objective. Since any real design solution, planned or existing, provides for a variety of flight objectives, there will be a range of inflation factors associated with any real design. With the ideal wing regarded as the hypothetical aerodynamic ideal, the inflation factor is a measure of design quality as it reflects the departure from the ideal. The inflation factor should strive towards 1, and for small deviations from 1, the flying wing could be a practical solution. Junkers' Volume Patent gives priority to such solutions. Therefore, to evaluate the merit of this idea, one needs only to estimate the inflation factor of real flight objectives.

Real solutions deviate from the ideal due to technical constraints. A wing of lower AR than that of the ideal wing is inflated due to the lower AR and the operation at a lower C_L. Deviation from the elliptical planform may lead to inflation if a small taper ratio is used. A general equation for wing density is (combining Equations (8), (10) and (12)):

$$\rho_{Wing} = \frac{m}{f_{PT} f_{AF} t} \sqrt{\frac{AR}{S^3}} \quad \ldots (23)$$

3.0 INTERPRETATION

When considering an existing aircraft design (or one in development) the aircraft volume is in principle known and the range of mean aircraft density is simple to derive. From the corresponding ideal wing density the *inflation factor* can then be derived for a given flight objective. The inflation factor can then be used directly to establish which combination of cruise speed and air density would offer an inflation factor of 1 (or close to 1) for the wing volume to be useful. If the resulting operational parameters are acceptable, implementation of Junkers' Volume Patent may be considered for the given flight objective. More important, however, may be to observe the historic trend in technological capabilities and operational preferences to ascertain whether aircraft development is moving towards or away from the idea of the Volume Patent. This will reveal the favoured family (i.e. *classical* or *integrated)* from which the aircraft of the future may emerge.

The significant parameters of *wing density* will now be discussed in terms of their historical trends. Trends increasing the wing density of real wings drive development away from the idea of Junkers' Volume Patent. With $\rho_{Wing} = f(\sqrt{C_L^3 AR/t})$, the trend in aerofoil development does just that.

Improvements in laminar aerofoils favour a higher design C_L and offer a lower design c_d and tend towards lower thickness t. These improvements call for an increase in the design AR

which technological advances in materials and structural strategies also allow. Together such implementations impose a strong penalty on wing volume.

Even more diverting has been the increase in cruising speeds given that $\rho_{Wing} = f(V^3)$. Early flight was limited to lower speeds. The gas turbine then pushed the common cruise speed to the fringes of the compressibility limit, where it is likely to stay. Given the profound effect of cruise speed on wing density, the integrated aircraft configuration may take advantage *if* the hurry-up-and-wait staccato of current air travel improves in other contributors to total travel time, to permit a slower flying speed in favour of more comfortable travel and arrival times with better flight economy.

Only the trends towards flight at lower air density at higher altitudes and towards heavier aircraft act in favour of the Volume Patent with $\rho_{Wing} = f(\sqrt{\rho^3/m})$. This explains why the integrated approach is mostly considered for large-capacity aircraft cruising at high altitude.

4.0 EXAMPLES

In this section, the parameters of ideal wing density and the inflation factor are used by example in two different ways. In one case, taken from the discipline of gliding, they are used to show how diverse the ideal wings can be for different mission segments within the same mission. A trend is noted and later related to the second example. This other example shows the domain in which the airline industry would have to operate efficient, integrated solutions.

4.1 The sailplane

The sport of gliding holds a special place in aviation development. Gliders were the first aircraft in human aviation and are still often used in aircraft development projects. Furthermore, the discipline of gliding still serves as an incubator for many developments in aviation. A sailplane has a particularly challenging mission family because the typical gliding flight frequently alternates mission segments having conflicting flight objectives. Most other aircraft can be specialised for their principal flight objective, but in gliding, such specialisation is not practical. The absence of an on-board power system makes the glider very relevant to the notion of the ideal wing in which the issues of propulsion are not addressed. Even though the energy for gliding flight is almost free, aircraft efficiency is of prominent importance in the context of competition flying. Gliding competitions, in turn, present an unrivalled platform for overall evaluation of design quality in which the full spectrum of quality issues is reflected.

What role can the idea of the ideal wing play in understanding the shape and the evolution of the sailplane? Consider the following questions: What does the ideal wing look like for the best rate of climb in a column of rising air? How does this wing compare to the ideal wing for the best straight gliding distance at high speed? How much space for the pilot (the occupants) or ballast would these ideal wings offer? How do real solutions compare to the various ideal wings? What trends may be expected for the future of the sailplane? To which aircraft family does the sailplane of the future belong?

In line with the approach of dividing the mission into isolated mission segments, the take-off, the powered climb and the landing can be ignored, as the typical competition mission has its important mission segments between the start and the finish gate. Taking a flat-land

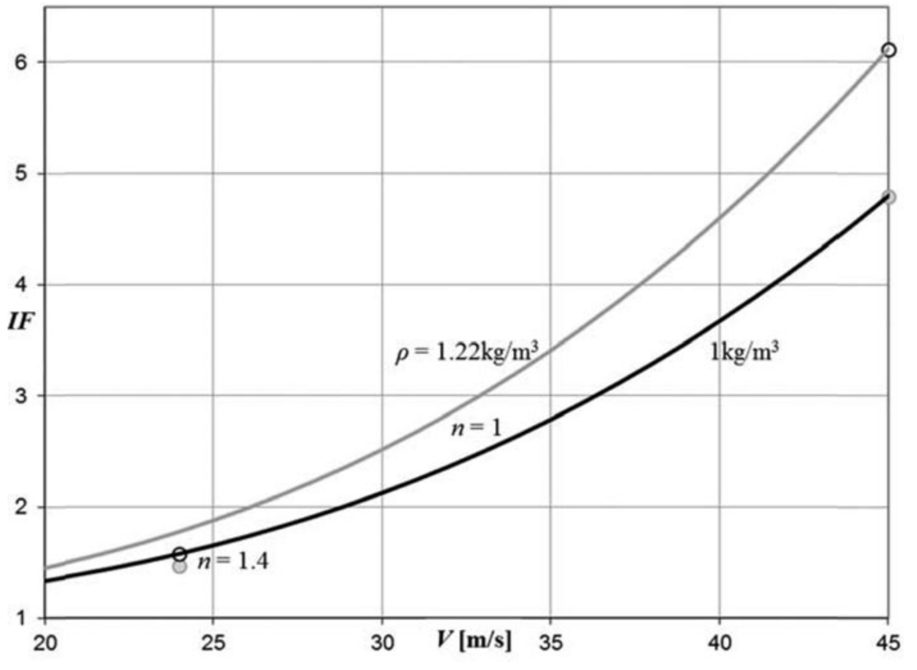

Figure 7. Inflation factor (*IF*) as a function of the design flight speed *V* for different air densities ρ and load factors *n* (based on the aerofoil parameters offered in the previous figures).

distance task in convective conditions as an example, there are two distinct mission segments which are alternately flown during the task. During the segment of climb in rising air, when the glider is taking aboard environmental energy, the flight objective is to exploit a local region of best rising air most efficiently. In terms of the competition objective, to cover the task distance within the shortest time, it is then the rate of climb that matters. The lower the flight speed and mass, the better. During the run segment, the best glide distance should be achieved in the shortest time and thus high speed and mass are of interest.

Operationally, the performance objectives of the two segments differ in that the climb should be flown at the speed for minimum sink rate, while the run should be flown at the speed for minimum drag. However, if specialising a wing by design for a specific desired speed, in both cases minimum drag is the design objective. That means that only the wing area (and thus the wing loading) will differ for the ideal wings of the different mission segments. The aerofoil can then be essentially the same, as Re does not vary, and thus the design c_l and c_d will also be the same. The only compensation needed is for Ma within the regime under consideration. The parameters as derived from Fig. 4 can then be used in this example.

All-up mass can be reduced by dumping ballast (if available), but no means of increasing it in flight is in common use. Therefore, the all-up mass is considered here to be the same for both mission segments, taking $m = 600$ kg. Thus, in this example only *V*, ρ and *n* remain as operational variables. The wing density (or the expected inflation factor) can then be plotted against speed as in Fig. 7, with typical low-speed flight shown at $n = 1.4$ (45° bank angle), while the high-speed flight is shown at $n = 1$ (straight flight). Air density is taken to vary between sea level density and that at 2000 m (1.22 and 1 kg/m^3, respectively).

The aspect ratio of 100 is the same for all such ideal wings and the largest root chord is then <200 mm, evidently insufficient for an occupant. Adding the minimum volume of about

0.5 m^3 required for an occupant to the volume of the ideal wing gives the inflation factor as plotted in Fig. 7.

The attractor towards low wing loading for the climb segment pulls the ideal wing towards the idea of the Volume Patent, while the opposing attractor for high wing loading pulls far from it. The low inflation factor solution is interesting in weak conditions when no record-breaking flights can be expected, while the dense wing can achieve record results in strong conditions, thereby setting the trend. This is demonstrated by unique sailplane developments like the *Concordia* and the *eta* that have *AR* tending towards that of their ideal wings with 50.3 and 48, respectively, unbraced! Their wings clearly show that the wing is useless for the occupant; their volumes are not even sufficient for the desired ballast (as can also be derived from the wing density).

The Horton *H IV* glider had remarkable performance under certain conditions when compared with other gliders of its time(3). The *H IV* was one of very few implementations of the idea of Junkers' Volume Patent, as the fuselage was essentially contained within the wing. However, its approach was not repeated when tailless gliding was given another chance with the *SB 13*, which instead offered a dedicated fuselage(4).

From these observations it would appear that the sailplane of the future will remain within the classical family.

A further comment can be made when considering the two extreme ideal wings of gliding. One might enquire why area-extending flaps are not common features on modern sailplanes(23), and, how and whether one might reconfigure a wing in flight for the two opposing flight objectives. This issue was at the heart of the projects *fs 29* of the Akaflug Stuttgart and the *SB 11* of the Akaflug Braunschweig(24). The *fs 29* used a telescopic wing to increase wing area and *AR* for slow flight while the *SB 11* used area-extending flaps by which, however, *AR* decreases as the wing area enlarges. The notion of the ideal wing suggests that the shape of the wing should ideally remain the same for both flight objectives; only its size should change. Implementation of such a strategy of in-flight wing adaptation is highly impractical. Therefore, either span or chord changes are considered independently for real solutions, and as long as this will be the case, consensus cannot be reached on which is the better compromise.

4.2 The airliner

Here, a modern commercial airliner, the *Boeing 787–800*, is taken as an example. Its fuselage volume is estimated to be about 1230 m^3 and its total volume is about 1585 m^3 (excluding the engines). With an all-up mass of 228,000 kg and an empty mass of 118,000 kg, the mean aircraft density will not exceed 144 kg/m^3 or be less than 74 kg/m^3. Taking the cruise segment of the mission as the principal mission segment and assuming that the displacement volume m/ρ_{Air} is about 553,900 m^3 while cruising at a constant true airspeed of 254 m/s, the mean aircraft density could vary between 132 and 92 kg/m^3 during the principal mission segment as fuel is burned off. In contrast, the density of the representative ideal wing for this flight objective varies between 550 and 383 kg/m^3. The inflation factor is then about 4.1 and this is a fixed value given that the flight objective defines an ideal wing of unique size. Thus, the volume of the ideal wing, like that of the real aircraft, is constant. An ideal wing useful for this flight objective would require ideal wing densities of the same order of magnitude as those of the real aircraft for the inflation factor to be 1 (or close to 1). With all else remaining the same, such a wing would have to cruise at $V_{787}/\sqrt[3]{IF} = 0.62V_{787}$, or at about 158 m/s, to have a wing volume sufficient to include the entire aircraft with its payload. Alternatively, the aircraft should cruise with a displacement volume of $\sqrt[3]{IF^2} = 2.57$ times larger. This could be achieved by cruising about 6000 m higher and at the same speed. The ideal wing would then have a root aerofoil thickness of about 3 m, perhaps sufficient for the payload grain size. These findings are in line with those of Torenbeek[9], who goes further in an exercise of optimisation to find the best combination of speed and density at which the flying wing could in principle be suitable.

5.0 CONCLUSIONS

While it may be qualitatively obvious how wing area, span, and aspect ratio influence the wing volume, the expressions for the volume of the wing box in Equation (12) help to quantify these dependencies explicitly. In surveying modern aircraft configurations, one will intuitively be inclined to dismiss the idea of Junkers' Volume Patent. However, alternatives to the current dominant configuration continue to be proposed and debated. The notion of the *inflation factor* as a property of a specific flight objective is useful in understanding the relative importance of wing and fuselage volume, and it may be the most decisive figure of merit for the choice of aircraft configuration. Indeed, it can easily be used as the single variable by which 'genetic' relationships between various configurations can be established. Its historic trend then also gives clear indications as to where aircraft development is heading or where it should go.

Inflation factors of the typical current flight objectives are much too high for Junkers' Volume Patent to be of interest. The technological trend in terms of structure and the design C_L are not expected to reduce the inflation factor. On the other hand, environmental and/or economic pressures may force the cruise velocity and air density to be lowered and mass to be increased in favour of lower inflation factors. Propulsion technology is likely to lead the way to lower cruise air densities. However, with the majority of principal flight objectives related to maximum range, it is extremely unlikely that the wing density will ever become compatible with payload density for any significant number of flight objectives. It is therefore concluded here that the prediction implicit in the Volume Patent will never be confirmed in an economically significant way. The majority of flight solutions of the future will require inflation factors significantly beyond 1 even though several future flight objectives are expected to have low inflation factors (given that miniaturisation of payloads is a prominent trend in unmanned aviation). Wing volume will remain useful for structure, fuel, and ballast, and elements of the propulsion system are likely to find their way into the wing, but bulky payload is expected to remain in a dedicated container of suitable shape.

The campaign for braced wings respects the attractor towards high AR and acknowledges that the volume of the ideal wing is rather limited – not even sufficient for the entire wing structure.

The magnitude of typical inflation factors hints that the classical dedicated wing body family is more likely to hold the configuration for the aircraft of the future. On this side of the binary configuration divide also resides the current dominant configuration and all proposed braced-wing configurations.

At the time that Junkers filed his patent, the gas turbine had not been foreseen, laminar flow aerofoils were not yet known, and material properties were far less advanced, so the inflation factors of the time were therefore much smaller and even showed a downward trend as aircraft grew in mass and size. Junkers therefore had all the right reasons for filing this patent. He would, however, most likely not have done so today.

ACKNOWLEDGEMENT

We would like to thank Loek Boermans (TU Delft) for his valuable comments and suggestions. We also thank referees for careful and constructive comments.

6.0 APPENDIX A

6.1. Planform transformation for tapered wings

With the *wing box* having the same base area of the wing $S = bc$ and a square longitudinal cross section (with longitudinal here making reference to the aircraft coordinate convention), its volume is:

$$Vol_{WB} = bc^2$$

and the transformed *tapered box* having the same base area S and retaining the square cross sections, the *taper transformation factor* is their volume ratio:

$$f_{PTT} = \frac{Vol_{TB}}{Vol_{WB}}$$

with the planform *taper ratio* being the ratio of the tip chord to the root chord $Z = c_T/c_R = e/d$ and, from Fig. A1, $e = d - b = Zd$ $d = b/1 - Z$ and $e = bZ/1 - Z$

The mean chord is $c = c_R + c_T/2$ or $c = c_R\,(1 + Z)/2$ so that $c_R = 2c/1 + Z$ and $c_T = Zc_R$

The volume of the *tapered box* is what remains of the pyramid after subtracting its tip:

$$Vol_{Pyr} = 1/3c_R^2 d = 1/3c_R^2 \frac{b}{1 - Z} \text{ and } Vol_{Tip} = 1/3c_T^2 e = 1/3c_R^2 Z^2 \frac{bZ}{1 - Z}$$

$$Vol_{TB} = Vol_{Pyr} - Vol_{Tip} = 1/3c_R^2 \frac{b\left(1 - Z^3\right)}{1 - Z}$$

so that the *taper transformation factor* becomes:

$$f_{PTT} = 1/3 \frac{4c^2}{(1 + Z)^2} \frac{b\left(1 - Z^3\right)}{1 - Z} \frac{1}{bc^2}$$

$$f_{PTT} = \frac{4\left(1 - Z^3\right)}{3(1 + Z)^2\,(1 - Z)}$$

6.2. Planform transformation for elliptical wings

The elliptic transformation transforms the rectangular *wing box* to a volume with an elliptical planform and square longitudinal cross sections (as above).

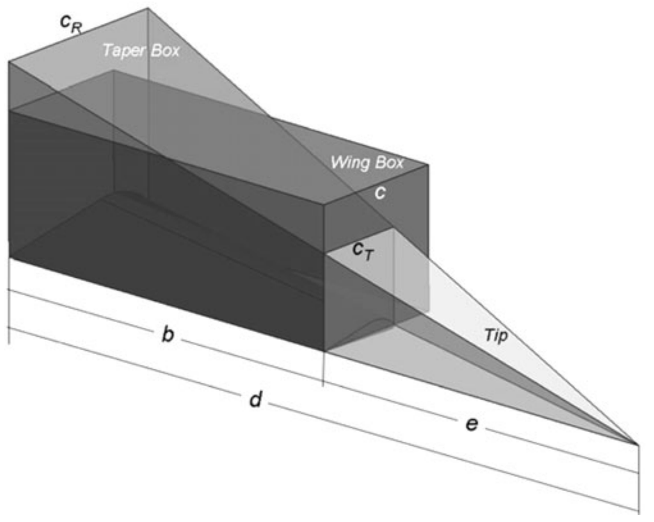

Figure A1. Wing box and the transformed wing box of a tapered wing.

If *i, j* and *k* are the principal dimensions of an arbitrary ellipsoid, then *i* and *j* could be the root chord c_R and *k* the span *b* of a round ellipsoid derived from a wing of elliptical planform. The volume of this ellipsoid would be:

$$Vol_{Ellipsoid} = 4/3\frac{\pi}{8}ijk = 1/3\frac{\pi}{2}c_R^2 b$$

The cross-section area of this ellipsoid in the plane of the wing has the same area as the elliptical planform of the wing, $S = bc$ with *c* the mean chord, thus:

$$S_{Ellips} = \frac{\pi}{4}ik = \frac{\pi}{4}c_R b = S = bc \quad \text{so that} \quad c_R = \frac{4}{\pi}c$$

The area of a square enclosing a circle of diameter *d* is larger than the circle area by the factor:

$$\frac{S_{Square}}{S_{Circle}} = \frac{4d^2}{\pi d^2} = \frac{4}{\pi}$$

Then, the volume of the round ellipsoid transformed to the *elliptical box*, a body of elliptical base section and square longitudinal cross sections is:

$$Vol_{PTE} = \frac{4}{\pi}1/3\frac{\pi}{2}\frac{16}{\pi^2}c^2 b$$

and, by definition:

$$Vol_{WB} = c^2 b$$

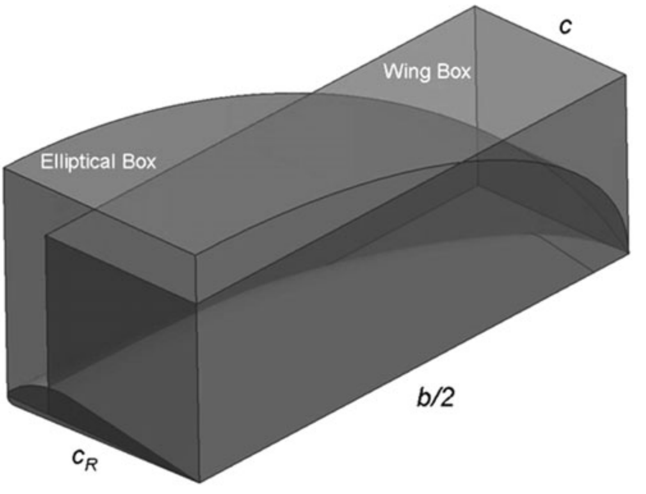

Figure A2. shows the wing box and the transformed wing box of an elliptical wing.

Then, the planform transformation factor to transform the *wing box* to the *elliptical box* is:

$$f_{PTE} = \frac{Vol_{PTE}}{Vol_{WB}} = \frac{32}{3\pi^2} \approx 1.08$$

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Pitch Handling Qualities Investigation of the Tailless Gull-Wing Configuration

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A handling quality analysis of the tailless swept gull-wing configuration is presented here. This aircraft configuration is defined, for the purpose of this discussion, as one having multiple sweep and dihedral angles. The effects of changes in the static margin and of gusts on handling qualities were investigated for this new configuration. The Exulans, an aircraft currently under development, was used as a representative example of a tailless swept gull-wing configuration. The Exulans uses variable outboard wing sweep as a means of static margin control. This is achieved by a sweep hinge located at semi-span. The pilot can change the outboard wing sweep angle for purposes of pitch trim. The Exulans is a research test bed that is being used to investigate the possibility of designing a tailless aircraft with both good handling qualities and a high Oswald efficiency. The handling qualities investigation was limited to the longitudinal plane. A Neal-Smith handling quality analysis was used to investigate handling qualities at different static margins while a Mönnich-Dalldorf analysis was used to investigate gust handling qualities. Time domain simulations were also used to investigate the aircraft gust response. It is shown that the gull-wing configuration promises to have satisfactory handling qualities for a region of *CG* locations for which good Oswald efficiency can also be achieved. A satisfactory gust response can also be achieved.

Nomenclature

CG	=	center of gravity
C_{De}	=	equilibrium drag coefficient
$C_{L\alpha}$	=	lift coefficient curve slope, 1/rad
$C_{L\delta e}$	=	lift coefficient due to elevator deflection, 1/rad
C_{Mq}	=	pitching moment coefficient of aircraft due to pitch rate, or pitch damping, 1/rad
$C_{M\alpha}$	=	pitching moment coefficient curve slope of the aircraft, 1/rad
$C_{M\delta e}$	=	pitching moment coefficient due to elevator deflection, 1/rad
d	=	neuromuscular time delay of a pilot
F_s	=	pitch control stick force, positive for pull, N
g	=	gravitational acceleration, m/s^2
K_p	=	steady state pilot gain
K_θ	=	'airframe only' gain
L	=	total aircraft lift, N
MAC	=	mean aerodynamic chord
m	=	aircraft mass, kg
n	=	aircraft load factor $L/(mg)$, or the normal acceleration of aircraft
S	=	aircraft wing area, m^2

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SM	=	static margin
s	=	Laplace variable, 1/rad
V_T	=	true airspeed, m/s
x_{cg}	=	distance from the leading edge of the wing on the aircraft longitudinal axis to the *CG* of the aircraft
ζ_{sp}	=	short period mode damping ratio
θ_e	=	error between the commanded pitch attitude and the aircraft pitch attitude, rad
θ	=	pitch angle, rad or degrees
ρ	=	air density, kg/m^3
τ_{p1}	=	time constant of control system lead element, s
τ_{p2}	=	time constant of control system lag element, s
$\tau_{\theta 2}$	=	numerator time constant (airframe lead time constant) of the elevator deflection to pitch rate transfer function, s
ω_{nsp}	=	short period mode natural frequency, rad/s

I. Introduction

THE tailless gull-wing configuration is an unconventional layout for aircraft but found on many fliers in nature. It is defined here as a wing configuration that has both multiple sweep angles as well as dihedral angles without tail wings dedicated for stability or control. The wandering albatross (*Diomedea exulans*) is an example of a bird that has such a wing configuration.

The gull-wing configuration is the focus of a research project [1]. This investigation is intended to include full-scale flight testing. For this purpose a test aircraft, the Exulans, is being developed. This test-bed is designed as a single seat ultra-light glider. Before test flying commences the anticipated flight properties should be well understood. This research investigates the trade-off between flight efficiency and handling qualities. It looks at various ways in which pitch control and pitch trim can be achieved without adverse effects on efficiency. For this reason the Exulans incorporates variable wing sweep on the outer wings as a means of static margin control for pitch trim.

For a new aircraft configuration to be justified, it should be superior in aerodynamic efficiency while having comparable handling qualities. Many other tailless designs such as the SB13 have shown shortcomings in their handling qualities [2]. Tailless aircraft have low aerodynamic pitch damping and pitch mass moment of inertia when compared to aircraft designs with an empennage. Therefore tailless aircraft have unique pitch dynamics that may affect the handling characteristics.

Established methods were used to analyze the handling qualities of the gull-wing configuration, using the Exulans as a specific example. The Neal-Smith analysis technique [3] was used to evaluate the pitch handling characteristics of the aircraft in calm atmospheric conditions. This technique was chosen since it uses a pilot model formulation, with which the pilot/aircraft interaction may be studied in a repeatable and controlled manner. The Mönnich-Dalldorff [2] criterion was used to evaluate the aircraft handling characteristics in gusty conditions. The handling qualities of the Exulans are also compared to the handling characteristics of an existing tailless and a conventional glider design.

II. The Swept Gull-Wing Configuration

The gull-wing configuration is unconventional so it can be compared with very few existing designs. Historical examples of aircraft with similar geometry include the Weltensegler [4] and its successor, the Charlotte [1], of Germany and the SZD-6x Nietoperz [5] of Poland.

The Exulans is presented schematically in Fig. 1. The inboard wing portion is swept forward and has dihedral, while the outboard section is swept backward and has anhedral. The outboard section of the wing has controllable variable sweep that is made possible with a hinge situated halfway between the wing root and the wing tip. The variable sweep of the outboard wings is used to control the longitudinal trim condition. This eliminates the need for deflecting a wing based control surface, which would adversely impact the span-wise lift distribution. The variable wing sweep allows the lift distribution to remain favorable throughout the operational speed range of the aircraft. Additionally it has the advantage that the useful range of the control surfaces is not compromised by trimming the aircraft, as is often the case with tailless aircraft that use only the elevons for longitudinal trim control. The outer wing sweep angle could be as high as 36° for fast flight and as low as 24° for slow flight, depending on the position of the *CG* for a given flight.

The Exulans uses elevons on the outboard sections for pitch and roll control, while the inboard portions contain flaps. Controllable winglets are situated on the tips of the outboard sections. These are primarily used for yaw damping and for directional control. The winglets can rotate to change their toe-out angles. The winglet toe-out angles are appropriately linked to the sweep angle while yaw control inputs are superimposed.

Like other tailless aircraft, the Exulans has low aerodynamic pitch damping and pitch inertia when compared to tailed aircraft designs.

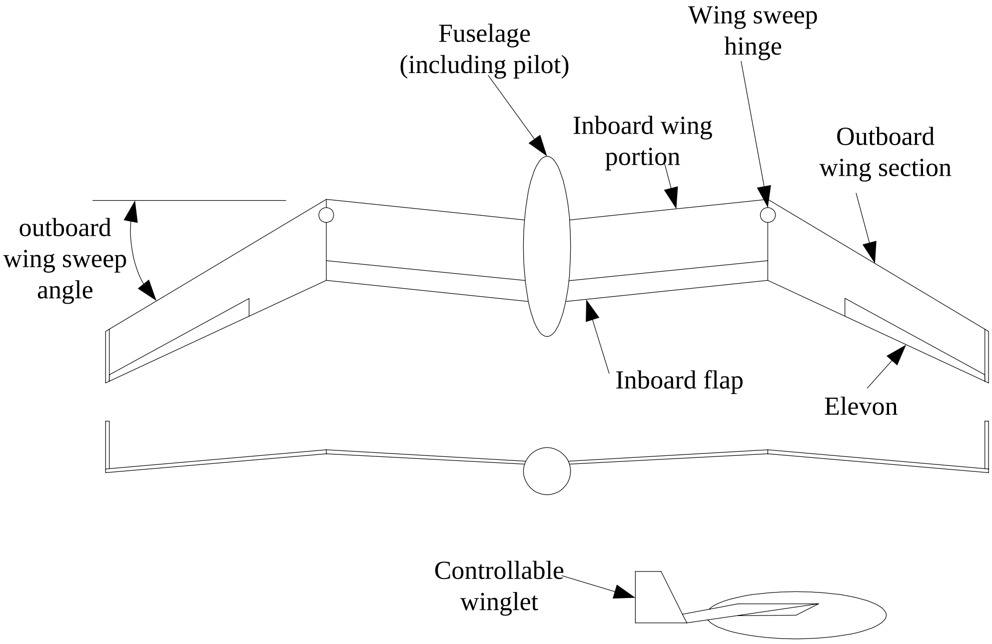

Fig. 1 Schematic of the swept tailless gull-wing configuration (plan-form view shown here with 30° outboard sweep).

III. Aerodynamic efficiency of tailless aircraft

The core challenge in tailless aircraft design concerns the trade-off between aerodynamic efficiency and handling. Therefore the design objective relating to efficiency will be summarized here. Two special longitudinal CG locations are of particular interest. These relate to the E-point and the O-point.

The E-point [4] is defined as the position of the center of pressure of a wing having an elliptical circulation distribution along its span. Such a distribution is required to maximize Oswald efficiency [6], a factor of the induced drag of the aircraft. It is therefore desirable to place the aircraft CG on the E-point since this would be required to achieve trimmed flight with the optimal circulation distribution.

The O-point [4] is comparable to the E-point but its definition relates to a wing with winglets. In this case according to Horstmann [7] the most favorable circulation distribution is elliptical from tip to tip of the winglets. This implies that the wing tips carry more circulation than would be the case without winglets.

On a swept back wing this would mean that the center of pressure lies further back. Therefore the O-point would lie behind the E-point of the same wing without winglets.

The Exulans has winglets, however their primary function concerns yaw damping and yaw control. If they can additionally improve the effective span, the Oswald efficiency and thus the induced drag would improve. In the ideal case the winglets would be providing circulation as suggested by Horstmann [7]. Trimmed flight would then require the CG to coincide with the O-point. If handling qualities allow the associated static margin, then flight with the CG at the O-point would be possible. If however the winglets do not contribute to the effective span, then the best circulation distribution would be comparable to that associated with the E-point (as if the aircraft has no winglets). Therefore the region between the E-point and the O-point would represent desirable CG locations with wing efficiency potentially at its best with the CG at the O-point. Depending on the outcome of the handling quality study a designer can select an appropriate winglet toe-out angle and twist to provide the best circulation distribution with the center of pressure perhaps somewhere between the E and the O-point.

Another center of pressure location of interest has an indirect implication on efficiency. This is the C-point [4], the center of pressure associated with constant local lift coefficients along the span. A wing which would be configured to produce the maximum circulation along the span would have the lowest possible stall speed. Since wing size depends directly on the stall speed requirement the smallest possible wing would need to be flown with the CG in the C-point when requiring the lift coefficient to be high. If handling qualities permit, the wing size could be minimized in favor of lower parasitic drag.

The locations of the E-, O- and C-point, like that of the neutral point all depend on the wing (and winglet) plan-form and therefore vary with the outer wing sweep angle. Their locations can be closely approximated via the wing geometry if one assumes that the centers of pressure of the local wing sections are located at the local quarter chord position. This approximation would be acceptable if the section pitching moment coefficients are small as would generally be the case for the wing sections used on tailless aircraft wings. The position of the neutral point has to be found by numerical means. In this study a vortex lattice method was employed [8]. The winglets were included in the numerical model. Also the CG of the aircraft changes with sweep angle, because of the mass of the outer wing and the winglet, but at a smaller rate.

The results of the E-, O- and C-point calculations for the range of sweep angles of the Exulans are presented in Fig. 2. The figure also shows the location of the neutral point for different values of wing sweep. It can be seen that the C-point is almost coincident with the neutral point for the whole range of sweep angles. The E-point is ahead of the neutral point (or at a positive static margin). The O-point is aft of the neutral point for the whole range of sweep angles. Flight with the *CG* in the O-point would thus be done with a small negative static margin.

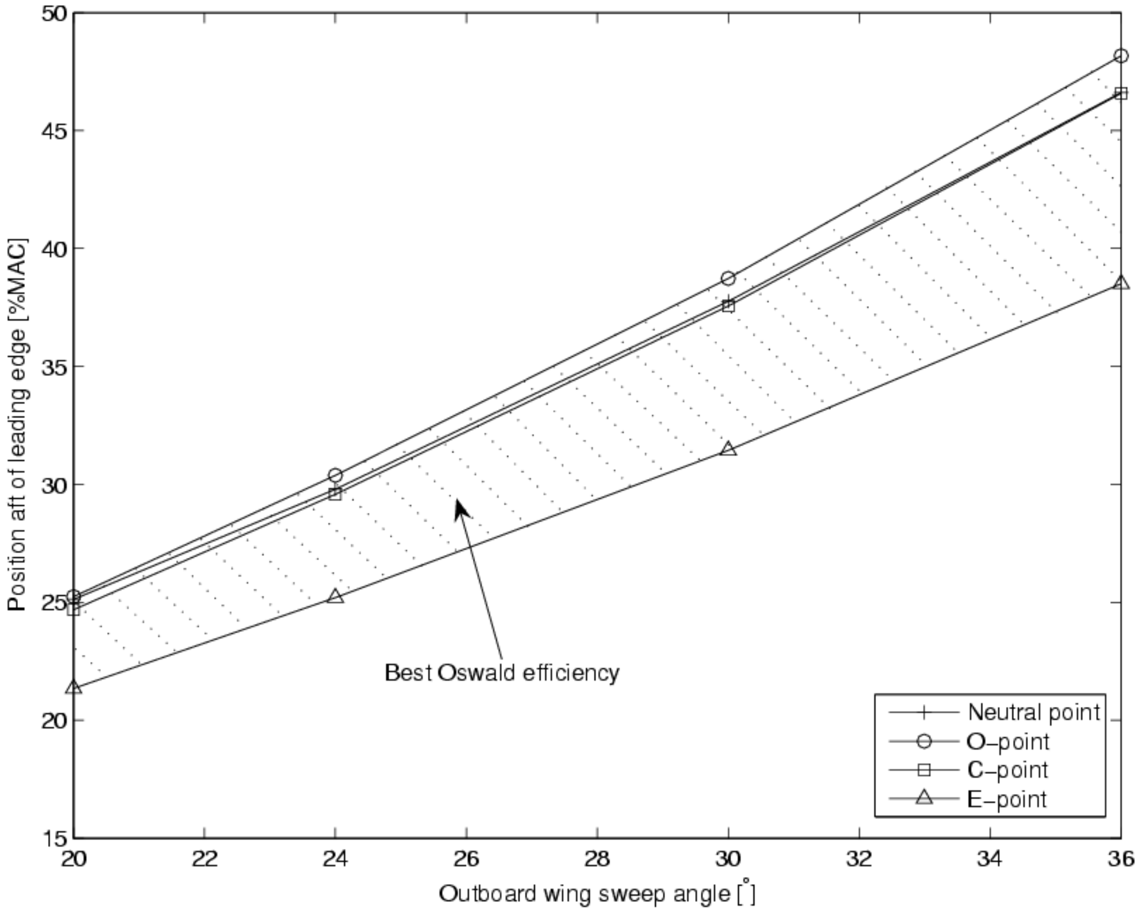

Fig. 2 Positions of the O-, E- and C-point and neutral point against the wing sweep angle for the Exulans. The region between the E- and the O-point would represent CG locations for best Oswald efficiency depending on the contribution by the winglets to the effective span. The y-axis represents the distance behind the wing leading edge at the plane of symmetry.

IV. Handling Quality Investigation at Different Static Margins with a Pilot-In-The-Loop Model

The Neal-Smith method [3] was used to evaluate aircraft handling characteristics at different static margins with a mathematical pilot model in the loop. A range of static margins (and thus CG locations) has been defined for desirable aerodynamic efficiency. Now the handling qualities have to be evaluated for this range of static margins. This is done to find the most desirable static margins in terms of the handling qualities. This investigation was used to ascertain whether or not a common region exists in which both efficiency and handling qualities are desirable.

A pilot in the loop was required to investigate the effect of a pilot in a controlled and repeatable manner. When the pilot transfer function is cascaded with the airframe transfer function inside a feedback loop as shown in Fig. 3, the closed loop transfer function has very different characteristics compared to the airframe model in isolation.

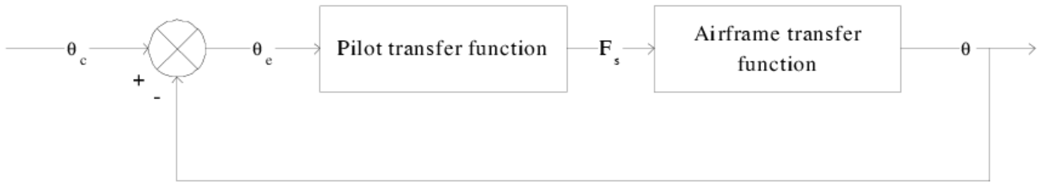

Fig. 3. Control closed loop diagram of the pilot and airframe.

The generic pilot model transfer function used with the Neal-Smith method is presented in Eq. 1.

$$\frac{F_s}{\theta_e} = K_p e^{-ds} \frac{\tau_{p_1} s + 1}{\tau_{p_2} s + 1} \tag{1}$$

The K_p variable in the equation above is the steady state gain of the controller. In this case the controller is not an automatic device (such as an autopilot), but the human pilot. In practice, the pilot gain will not be constant over the whole flight, but would vary in different flight conditions, based on the pilot's discretion. The variable '*d*' is a time delay. This models the reaction time of the pilot. The time delay incorporates the time to sense the need for action, the time to make a decision as well as the neuromuscular lag of the human body [3]. The value of 0.3 was used for the time delay parameter in the analysis done by Neal and Smith. The same value was used for the study on the Exulans.

The pitch control stick force to pitch attitude transfer function [9] shown in Eq. 2 was used to model the airframe. The airframe transfer function was created by using stability derivatives to calculate the short period natural frequency and short period damping ratio. The stability derivatives for the Exulans were calculated using a vortex lattice method [8]. The stability derivatives were calculated for a range of different sweep angles.

$$\frac{\theta}{F_s} = \frac{K_\theta \left(\tau_{\theta_2} s + 1\right)}{s\left(\dfrac{s^2}{\omega_{n_{sp}}^{\ 2}} + \dfrac{2\zeta_{sp}}{\omega_{n_{sp}}} s + 1\right)} \tag{2}$$

Eq. 3 shows how the airframe gain, K_θ, of Eq. 2 was calculated [3].

$$K_\theta = \frac{g}{V_T \left(F_s / n\right)_{SS}} \tag{3}$$

The preferred value of $(F_s/n)_{SS}$ for the pilots involved with the tests of [3] was between 20 to 31 N/g. The average value of 25.5 N/g was chosen for the analysis of the Exulans.

The Neal-Smith method assumes that the human pilot adjusts his own lead, lag and gain so as to minimize the droop and peak of the frequency response. This process is modeled mathematically by adjusting the lead and lag time constants in Eq. 1 to optimize the closed loop frequency response. This is done by minimizing the droop and peak of the system's Bode plot. The maximum lead or lag provided by the 'pilot' is then determined from this calculation and plotted on a pilot opinion chart (see Fig. 4) that has been created by flight testing [3]. A standardized pilot opinion rating is then read off the graph on which the calculated data has been plotted. This pilot rating (*PR*) is based on the Cooper-Harper pilot rating scale [10].

The Neal-Smith method was applied to different configurations of sweep and static margin of the Exulans. The different configurations are presented in Table 1. The handling qualities were evaluated for low, medium and high sweep angles. Each sweep angle was evaluated at low and high static margins. Even though the aircraft is statically unstable at negative static margins, it is necessary to investigate whether the combination of the pilot and the aircraft will lead to a total system with acceptable handling qualities.

Table 1 shows the static margin of the aircraft at the given sweep angle as well as the static margin that the aircraft would have if the wings were swept at 30° as a reference. 30° was chosen as a reference because this is the design cruise sweep angle.

Table 1. Exulans configurations used in the Neal-Smith handling quality evaluation

Sweep	Static margin classification	Static margin	Static margin reference
24°	Very low	-2.8%	2% at 30°
24°	Low	0.2%	5% at 30°
24°	High	10.2%	15% at 30°
30°	Low	5.0%	5% at 30°
30°	High	15.0%	15% at 30°
36°	Low	10.3%	5% at 30°
36°	High	20.2%	15% at 30°

The results of the Neal-Smith analysis for the different configurations listed in Table 1 are presented in Fig. 4.

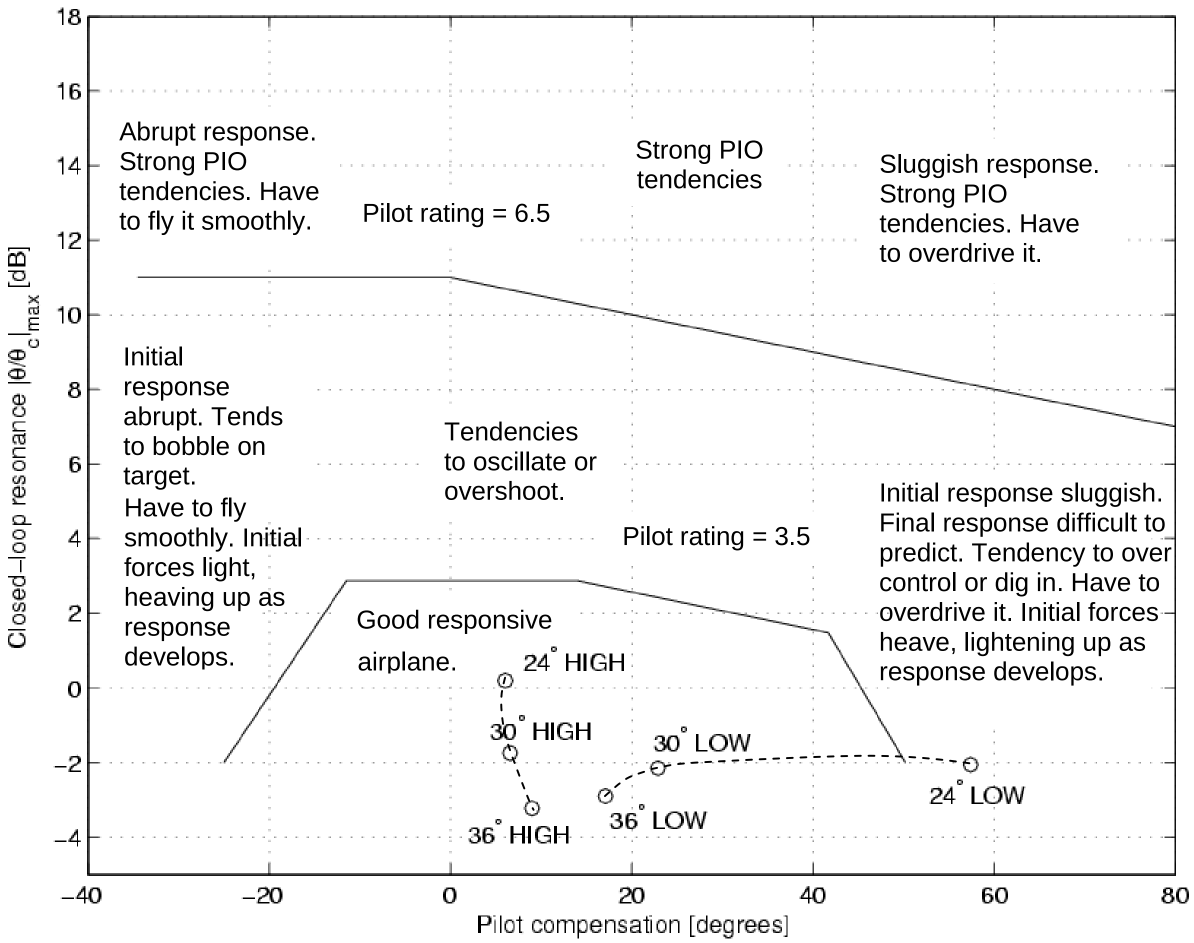

Fig. 4 Plot showing Neal-Smith analysis results.

Fig. 4 indicates that the Exulans has satisfactory handling characteristics with the pilot in the loop for a wide range of sweep angles and static margins. Handling qualities start to deteriorate with a combination of low sweep angle and low static margin. The lead and lag time constants in Eq. 1 of the configuration having the negative static margin (labeled "very low" in Table 1) could not be adjusted to meet the Neal-Smith criteria and therefore this configuration could not be plotted in Fig. 4. The same was found for other cases of negative static margin. This suggests that the Exulans handling qualities become unacceptable with static margins of less than zero. It is noteworthy that the Neal-Smith criteria was only correlated with flight test results until -2dB. Fig. 4 indicates that two configurations fall outside the -2dB range, but within the acceptable pilot compensation angle. Strictly speaking the Neal-Smith criteria can’t be applied to these two configurations. The general trend of the flight test data of the Neal-Smith criteria seems to indicate that pilot opinion got better with a lower closed-loop resonance. If this trend is extrapolated, it stands to reason that the configurations with less than 2-dB closed loop resonance (but within the acceptable pilot compensation limits) have acceptable handling qualities. This does require flight testing for verification.

V. Handling Quality Investigation for Gusty Atmospheric Conditions

The Mönnich-Dalldorff flying quality criterion [2] for tailless aircraft was used to evaluate the handling qualities of the gull-wing configuration in gusty atmospheric conditions. The method comprises the evaluation of the inequality presented in Eq. 4 for a given aircraft configuration to check whether or not it will have satisfactory handling qualities in gusty conditions. If the inequality is satisfied, the aircraft configuration should have satisfactory handling qualities in gusty conditions.

Satisfaction of the inequality guarantees that the vertical gust velocity to pitch attitude transfer function has a left plane zero. If this is not the case, the transfer function has a right plane zero. This also means that the aircraft phase response is non-minimum. The phase of the response could be out of phase with gust inputs by as much as 180°. This makes it extremely difficult for the pilot to be able to damp the aircraft response magnitude with elevator/elevon inputs as the phase shift of the response makes it difficult to judge the direction of the gust disturbance. The result of a right plane zero from the gust response transfer function is that the pilot will most likely cause pilot induced oscillations instead of damping the magnitude of the gust response during gusty atmospheric conditions.

$$\frac{C_{M_\alpha}}{C_{M_q}} < \left(C_{L_\alpha} + C_{D_e}\right)\frac{\rho S\left(MAC\right)}{2m} \tag{4}$$

The magnitudes of the stability derivatives in Eq. 4 were calculated using a vortex lattice method [8]. The Mönnich-Dalldorf analysis was performed at sea level density and 12000ft for international standard atmosphere conditions. The analysis was performed for several cases of wing sweep and static margin to investigate the different possible configurations of the Exulans. The static margin is specified by means of the reference static margin at 30° as was done in section IV. The 2%, 5%, 10.7% and 15% at 30° sweep reference static margin configurations were analyzed for 24°, 30° and 36° of outboard wing sweep. The analysis was also performed on the ASW-19 as well as the SB-13 in order to provide reference analysis results. The ASW-19 is an example of a standard class tailed glider. The analysis of the ASW-19 is useful for comparative purposes between tailed and tailless gliders. The ASW-19 has good gust handling characteristics at all altitudes according to the Mönnich-Dalldorff analysis [2]. This is in agreement with the general pilot opinion of the aircraft. The SB-13 is also a standard class glider, but tailless and has satisfactory handling characteristics in calm atmospheric conditions, but unsatisfactory handling characteristics in a gusty atmosphere according to the Mönnich-Dalldorff analysis. This analysis is in agreement with the flight tests that were performed on the SB-13 [4].

The results for the different sweep and static margin cases are presented in Tables 2 to 6. The results of the analysis performed on the ASW-19 and the SB-13 are shown in Table 7. The abbreviations "LH" and "RH" in these tables refer to the left-hand side and the right hand side of the inequality presented in Eq. (4).

Table 2 Constants used in the Mönnich Dalldorff analysis for the gull-wing configuration

Sweep	C_{Mq}	$C_{L\alpha}$	C_{De}
24°	-1.218	5.232	0.040
30°	-2.035	5.146	0.019
36°	-3.097	5.031	0.016

Table 3 Mönnich Dalldorff analysis for 2% static margin at 30° sweep configurations

Sweep	$C_{M\alpha}$	LH	RH Sea level	Inequality satisfied	RH 12000 feet	Inequality satisfied
24°	0.148	-0.121	0.247	Yes	0.172	Yes
30°	-0.103	0.051	0.242	Yes	0.169	Yes
36°	-0.365	0.118	0.236	Yes	0.165	Yes

Table 4 Mönnich Dalldorff analysis for 5% static margin at 30° sweep configurations

Sweep	$C_{M\alpha}$	LH	RH Sea level	Inequality satisfied	RH 12000 feet	Inequality satisfied
24°	-0.011	0.008	0.247	Yes	0.172	Yes
30°	-0.257	0.117	0.242	Yes	0.169	Yes
36°	-0.518	0.157	0.236	Yes	0.165	Yes

Table 5 Mönnich Dalldorff analysis for 10.7% static margin at 30° sweep configurations

Sweep	$C_{M\alpha}$	LH	RH Sea level	Inequality satisfied	RH 12000 feet	Inequality satisfied
24°	-0.309	0.182	0.247	Yes	0.172	No
30°	-0.551	0.216	0.242	Yes	0.169	No
36°	-0.804	0.217	0.236	Yes	0.165	No

Table 6 Mönnich Dalldorff analysis for 15% static margin at 30° sweep configurations

Sweep	$C_{M\alpha}$	LH	RH Sea level	Inequality satisfied	RH 12000 feet	Inequality satisfied
24°	-0.531	0.268	0.247	No	0.172	No
30°	-0.772	0.267	0.242	No	0.169	No
36°	-1.018	0.251	0.236	No	0.165	No

Table 7 Mönnich Dalldorff analysis for the ASW-19 and the SB-13

$C_{M\alpha}$	C_{Mq}	$C_{L\alpha}$	C_{De}	LH	RH Sea level	Inequality satisfied	RH 12000 feet	Inequality satisfied
				ASW-19				
-0.633	-17.680	5.917	0.013	0.036	0.086	Yes	0.060	Yes
				SB-13				
-0.590	-5.370	5.470	0.010	0.110	0.073	No	0.051	No

Table 8 Additional data for the ASW-19, the SB-13 and the Exulans used for the analysis in the tables above

Aircraft	S [m^2]	m [kg]	MAC [m]
ASW-19	11.8	408	0.82
SB-13	11.8	435	0.80
Exulans	12.0	160	1.02

The results show that the Exulans is likely to have satisfactory gust handling qualities at 24°, 30° and 36° outboard wing sweep at low altitude and low static margin. The Exulans is expected to have degraded handling characteristics in gusty atmospheric conditions at high altitude.

VI. Comparative Gust Response Simulation Results

Time domain simulations were performed to make a qualitative evaluation of the Exulans handling qualities. The aircraft pitch response with respect to a gust input was used to gauge its handling qualities. The simulations were performed using linear aerodynamics, except for the non-linear drag polar. The equations of motion for small disturbance theory [11] were used in the simulation.

The comparative simulations used the results of gust response simulations for three Exulans configurations, as well as simulations with the SB-13 and the ASW-19.

An Exulans configuration with low outboard wing sweep (24° sweep angle) and one with high wing sweep (36°) were used for the comparative simulation. A cruise configuration (30°) was also simulated. The 24° and 36° sweep cases had reference static margins of 15% and 5% respectively at the reference sweep angle of 30° giving them absolute static margins of 10.2% and 10.3%. These static margin cases were chosen for comparative purposes with the ASW-19 and SB-13, both which had a static margin of 10.7%. The 30° sweep case had an absolute static margin of 2%. This case was chosen to investigate the gust response at low static margins. The Exulans has a lower design speed than the other aircraft used in the comparative study, making a direct or quantitative comparison difficult. The Exulans models were trimmed at 55.3, 82.4 and 109.4km/h for the 24°, 30° and 36° sweep cases respectively. Both the ASW-19 and the SB-13 were trimmed at 120km/h for the simulations.

A simulation with a 10s duration was performed with each of the aircraft models. A gust that produces a nose down rotation (in other words a vertically upward gust) was introduced as a disturbance at 1s into the simulation. The gust has a 1 – cos shape. The gust model is similar to that used in [2]. The gust had a 2 m/s magnitude and a wavelength of 50 m for all cases. The time duration of the gust varied with the true airspeed of the aircraft. In the case of the ASW-19 and SB-13, the gust duration was 1.5s. The gust durations for the Exulans simulations are different due to the lower trim speeds.

The results of the simulations are presented in Figs. 5 and 6. The pitch attitudes of the different aircraft are shown as a function of time. Zero degrees is used as an arbitrary reference for the trim attitude for ease of comparison. Short period response is visible for all aircraft while exposed to the gust. The short period mode is rapidly damped out and the phugoid response follows.

The ASW-19 shows a short period mode with high subcritical damping (ζ_{sp} higher than 0.7, but less than 1). In comparison with the ASW-19, the SB-13's short period mode is less damped. The short period motion continues after the gust has been passed. The Exulans also shows a less damped short period in both the 24° as well as the 36° wing sweep case. The short period motions of these simulations are similar to the SB-13. The 24° wing sweep case also displays a large phugoid amplitude, but since the phugoid mode has a low frequency, this does not influence the handling qualities negatively. In contrast with the 10% static margin cases, the 2% static margin case with 30° sweep of the Exulans shows short period behavior that is comparable with the ASW-19 (see Fig. 6). These simulations show that the low static margin case of the Exulans has a more favorable short period response than its high static margin counterparts, since the short period mode is better damped for this case.

The short period mode is very important with respect to the handling qualities of an aircraft. It stands to reason that if it is well behaved, the aircraft should have satisfactory handling qualities. The ASW-19 acts predictably as it enters a gust. The SB-13 continues to oscillate after it has been excited by the gust. This makes it difficult for the pilot to anticipate and counter the motion of the aircraft, since gusts are usually random in nature. If the aircraft is still responding to a previous gust while being excited by the next, it is increasingly difficult for the pilot to identify the direction of the disturbance and to apply the appropriate counter for it. If the pilot is unable to do this, he/she may very well be amplifying the motion, rather than damping it.

In summary, a low static margin (2%) yields a more favorable gust response for a gull-wing configuration like the Exulans. This agrees with the work of Mönnich and Dalldorf who found that the SB-13 had improved gust handling qualities at 2% static margin [2].

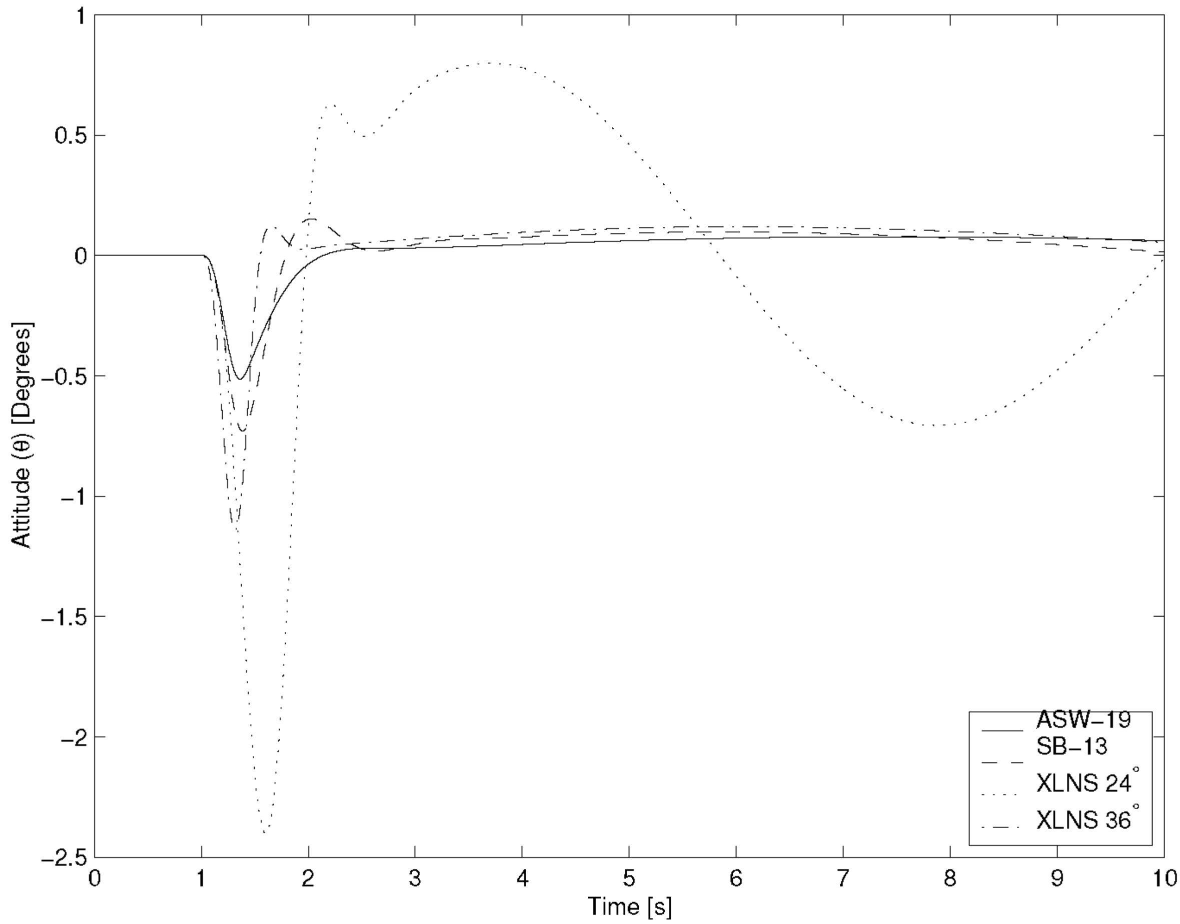

Fig. 5 The response in aircraft attitude (*θ*) to a 1−cos gust for the ASW-19, the SB-13, the Exulans with 24° and 36° sweep, all with static margins just more than 10%.

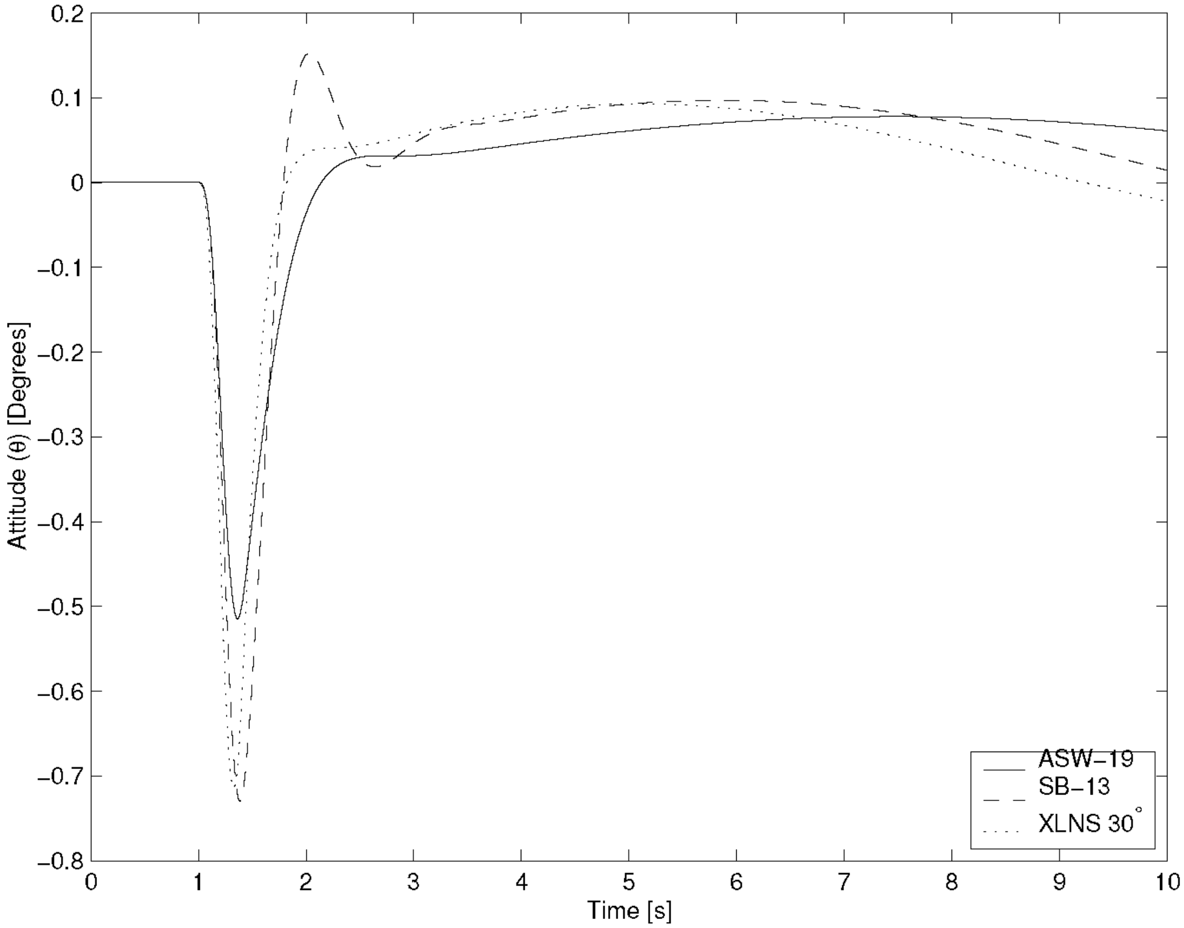

Fig. 6 The response in aircraft attitude (θ) to a 1−cos gust for the ASW-19, the SB-13 (both at 10.7% static margin) and the Exulans with 2% static margin and 30° sweep.

VII. Aerodynamic Efficiency in the Context of Handling Qualities

In this section the results of the two handling quality analyses are summarized and superimposed with the efficiency requirements discussed in Section III. This provides insight into the compromise between handling and efficiency relating to the gull-wing configuration.

The region of *CG* locations associated with the best Oswald efficiency lies between the E-point and the O-point of the aircraft, depending on the contribution that the winglets may be making to the effective span. This region is presented in Fig. 2 as the shaded area. The region of longitudinal *CG* locations associated with the most favorable handling qualities is presented as a shaded area in Fig. 7. This region is truncated at the low sweep angles, as these do not provide for trimmed flight. Fig. 7 also shows how the *CG* of the aircraft would change with a change in sweep angle given that the outer wings and the winglets are not without mass. Four different *CG* scenarios are plotted.

Fig. 8 shows the overlapping region of favorable handling qualities with the region of best Oswald efficiency. The overlapping region represents possible *CG* locations that would result in a *CG* position for an aircraft with both good handling qualities and a high Oswald efficiency.

Fig. 9 shows the intersection of the regions of favorable handling qualities and good efficiency plotted again with four different *CG* scenarios.

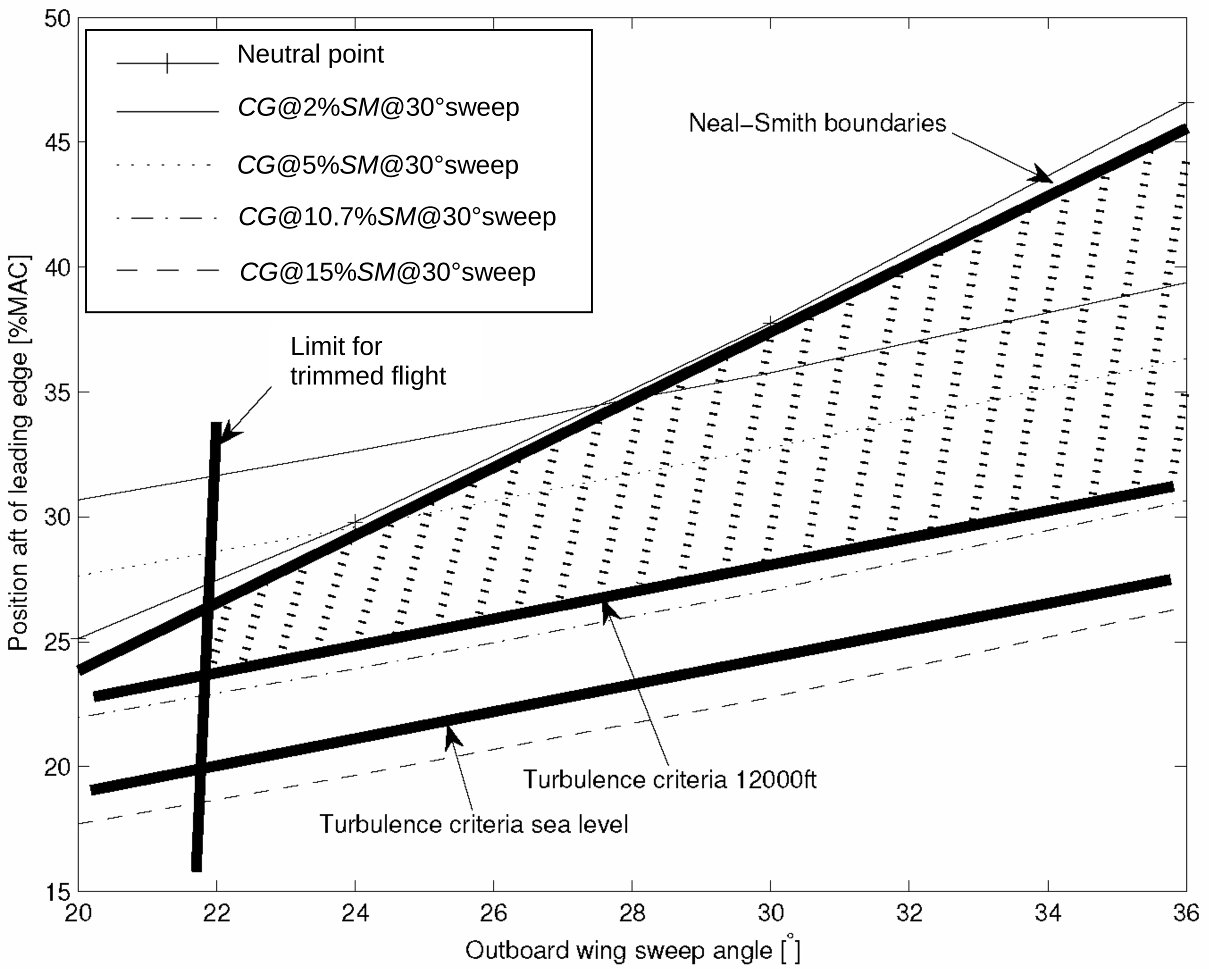

Fig. 7 Region of *CG* locations giving acceptable handling qualities (*PR* is 3.5 or better) for the Exulans for different sweep angles. The y-axis represents the distance behind the wing leading edge at the plane of symmetry.

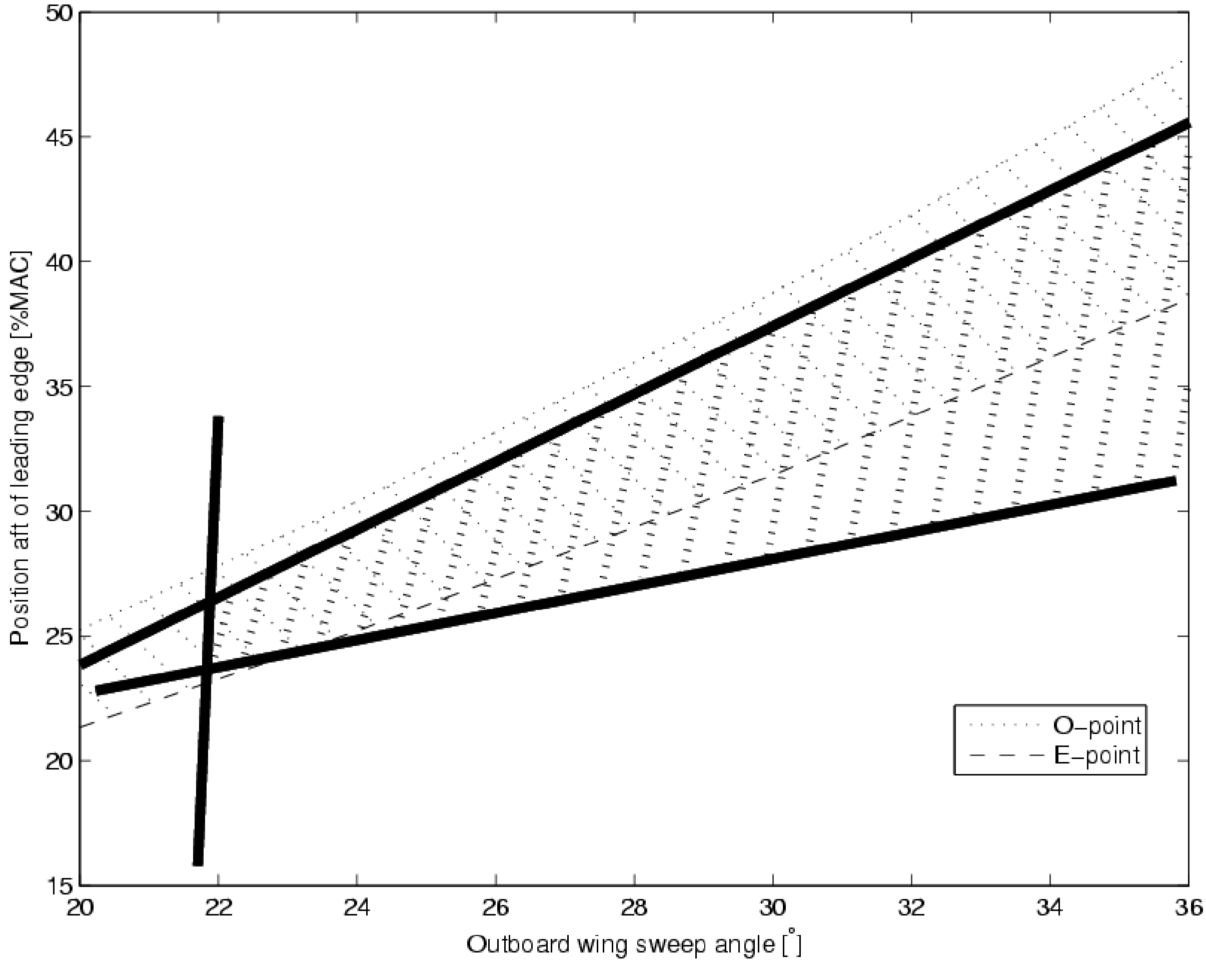

Fig. 8 Superposition of regions of CG locations giving acceptable handling qualities and best Oswald efficiency for the Exulans.

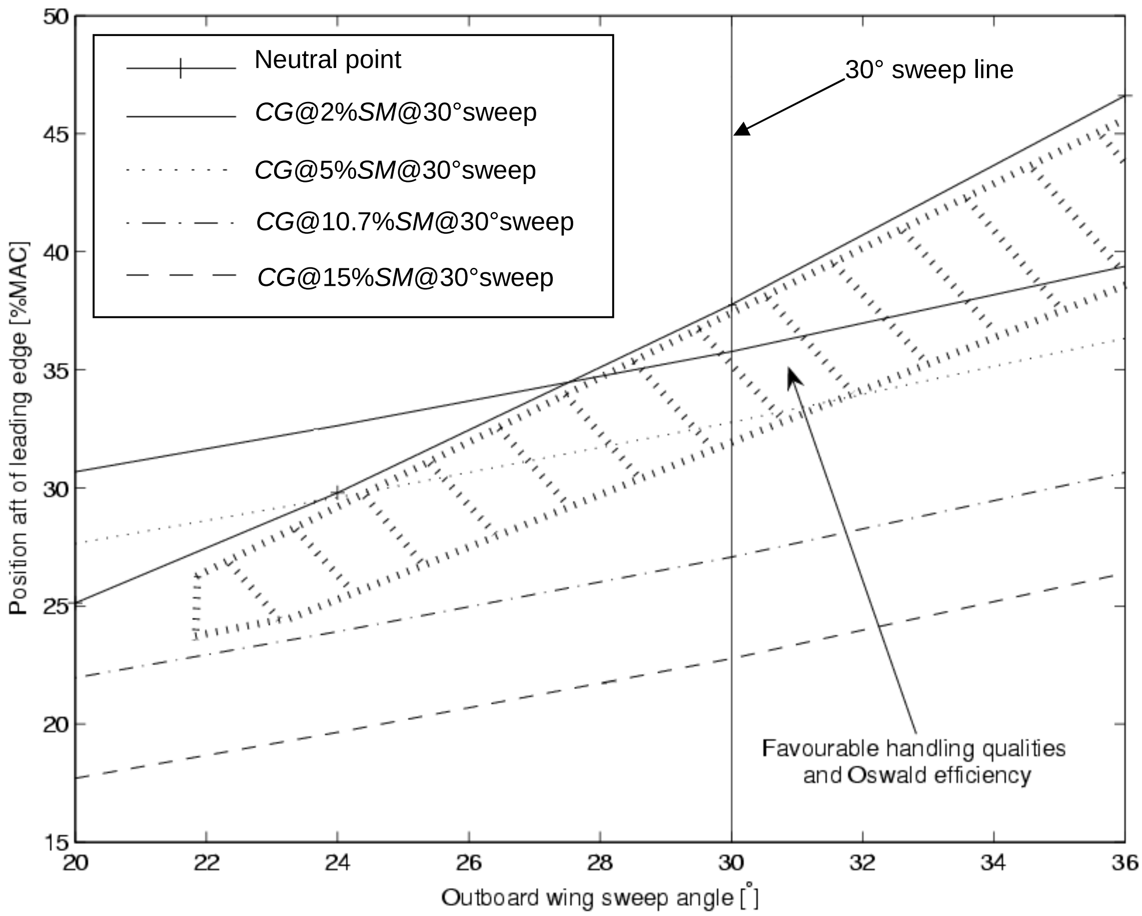

Fig. 9 Region of CG locations with both acceptable handling qualities and good Oswald efficiency for the Exulans.

VIII. Conclusion and Recommendations

A longitudinal handling quality analysis was performed on the gull-wing configuration. The subject of the analysis was the Exulans tailless glider. An analysis was performed using the Neal-Smith method as well as the Mönnich-Dalldorf flying qualities criteria for tailless aircraft. The following conclusions were drawn from this investigation:

- A region of *CG* locations exist for the tailless gull-wing configuration where the aircraft will have both favorable pitch handling qualities and high Oswald efficiency.
- It seems possible to design an aircraft with a gull-wing configuration that has acceptable longitudinal handling characteristics in a gusty as well as a calm atmosphere. The handling qualities of the Exulans

during gusty conditions should be good at low altitude but poor at high altitude (12000 feet) for the case of high static margins.

The following recommendations for further research can be made to better understand the handling qualities of the tailless gull-wing configuration:

- The handling quality analysis should be extended to lateral dynamics for a range of *CG* locations.
- The handling quality analysis results presented here cover only angles of attack in the linear lift region of flight. The pitch handling quality study should be extended to extreme angles of attack. Such a study should be used to investigate the handling qualities of the gull-wing configuration during recovery from flight conditions such as stalls and spins for a range of *CG* locations.

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Wing–Body Circulation Control by Means of a Fuselage Trailing Edge

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Ideal flight sheds the least amount of kinetic energy into a wake while imparting momentum sufficient to balance the vehicle weight. This combination defines a unique downwash distribution for the wake, which an aircraft designer should provide for. A central fuselage, as required for the typical flight objective, presents an obstacle to this intent. A wing interrupted by a prominent fuselage is expected to shed inboard trailing vortices with central upwash harmful to the span efficiency of the aircraft. It is proposed here that a trailing edge on the fuselage can be used to control the circulation in the central region of the aircraft so that the central downwash deficiency can be avoided. Such a Kutta edge can further be applied as part of a high-lift system to increase central downwash by increasing the loading on the wing root and lift over the fuselage itself. Time-averaged flowfields behind a wing–body combination with and without a Kutta edge have been measured in wind-tunnel experiments. The results show that an edged aft-body does influence central circulation, as predicted. Flight with ideal wakes may be more readily attained than hitherto realized.

Nomenclature

AR	=	aspect ratio
b	=	wing span, m
b_b	=	spanwise extent of body, m
C_D	=	coefficient of drag
C_L	=	coefficient of lift
c	=	wing chord, m
d	=	fuselage diameter, m
l	=	fuselage length, m
n	=	number of observations for time averaging
q	=	rms of fluctuating velocity magnitude, m/s
Re	=	Reynolds number
U	=	mean freestream velocity, m/s
u	=	streamwise velocity component (disturbance velocity, with U removed), m/s
$\bar{u}$	=	time average of velocity component, m/s
v	=	spanwise velocity component, m/s
w	=	vertical velocity component, m/s
$\langle w \rangle$	=	space averaged velocity component, m/s
α	=	geometric wing angle of attack, deg
δ	=	downward Kutta edge deflection angle, deg
Γ	=	circulation, m^2/s
ν	=	kinematic viscosity, m^2/s
ω_x	=	streamwise component of vorticity

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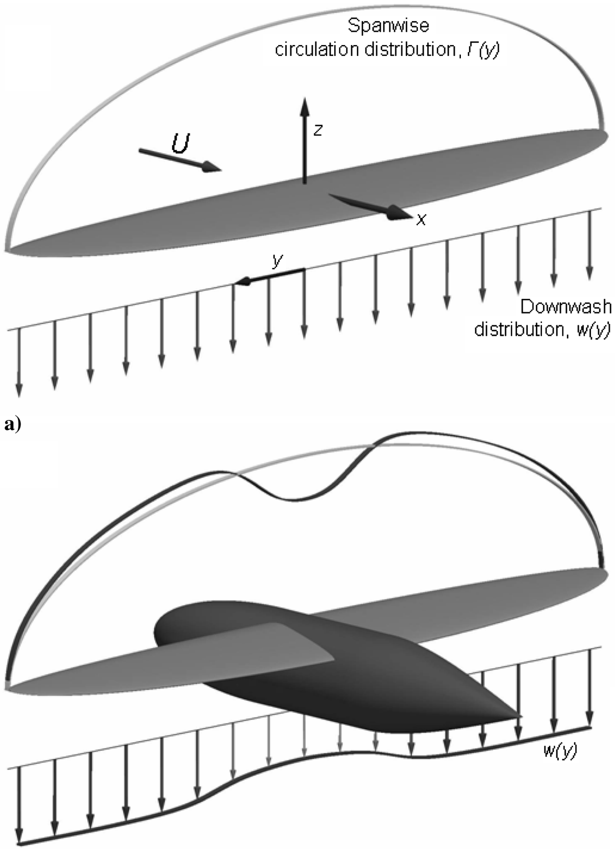
I. Introduction

THE wing with minimum induced drag has an elliptical circulation distribution $\Gamma(y)$ over the span so that the spanwise downwash $w(y)$ it induces is constant [1,2]. The flux of vertical momentum related to lift is determined by w, and the kinetic energy of the accelerated air is proportional to w^2. Therefore, the maximum momentum for minimum energy is transferred when $w(y)$ is constant, and it is simple to show that any deviation from this pattern must lead to a reduction in the lift-to-induced-drag ratio. The ideal aerodynamic shape for span efficiency of a lifting surface may therefore approximate an elliptical flying wing, with no other interfering parts (Fig. 1a). Practical flying devices must do more than occupy aerodynamic optima, and so compromises for stability and control and for carrying a payload lead to shapes in which the influence of the wing on the surrounding airflow is considerably altered by the presence of tail wings, flaps, engines, and a fuselage.

The most common arrangement for commercial transport is often termed the tube-and-wing configuration. The fuselage, shaped essentially like a long, streamlined tube, disrupts the wing. The fuselage itself is not usually designed to produce much lift, and the adverse effects of having the fuselage interfere with the wing must be tolerated as part of the design compromise. In this case, as shown in Fig. 1b, the fuselage is necessarily associated with local loss of lift ([3], pp. 11–18) and increased drag ([4], pp. 8–16). Figure 1b, analyzed in terms of either departure from constant $w(y)$ or the presence of additional streamwise vorticity, represents a more energetically wasteful solution than Fig. 1a. It would be better if the fuselage were not there.

Although the optimum aerodynamic shape for an aircraft could be that of a flying wing, the wing volume is generally insufficient to accommodate payloads of typical density and grain size ([5,6], pp. 13–16). It is possible to inflate the wing beyond aerodynamic necessity as in the various blended-wing–body (BWB) designs (e.g., [7]). However, as this approach is unsuitable for many flight objectives, this paper will retain the idea of a dedicated volume for payload, as in the typical tube-and-wing configuration. Normally, this fuselage has a flightwise length that is determined, in part, by stability and balance requirements, so that additional tail wings, both vertical and horizontal, will be mounted on the end of a relatively



a)

b)

Fig. 1 Schematic representation of a) an ideal- and b) a compromised spanwise distribution of circulation $\Gamma(y)$ and downwash $w(y)$, on the basis of equal wing lift.

long tail boom or fuselage extension. The consequences of relaxing this requirement will be investigated, assuming that stability and control can be provided without separate tail wings. (A rich history of tailless aircraft ([6], Chap. 12) various BWB designs and related research on this project show this to be possible [8].)

If the fuselage is not required to accommodate tail wings far behind the aircraft center of gravity, then it is likely to be shorter and larger in diameter while retaining the elliptical cross-section of the current dominant arrangement. McCormick ([9], Chap. 4, p. 165) summarizes data indicating a broad minimum in total volume-normalized drag coefficient for fineness ratios l/d between three and six. Therefore, provided that structural implications of pressurization are considered, a much broader design space of lower l/d shapes can be exploited. The shorter, wider body also allows new strategies for proximate circulation control on the body itself.

The following section will investigate the possible modification or tailoring of the body wake, to evaluate whether the optimal uniform distribution of $w(y)$ in Fig. 1a can be restored from its suboptimal state of Fig. 1b.

II. Shaping the Circulation Distribution

The wing–body aerodynamics can be described interchangeably either in terms of the spanwise circulation distribution $\Gamma(y)$ or the spanwise downwash distribution $w(y)$. The unique value of the local circulation on a lifting wing is determined by the Kutta condition at the trailing edge. If a prominent body interrupts the wing trailing edge, then the Kutta condition will not, in general, be maintained over the body itself, and the local circulation will change. (Defining a clear Kutta condition or an expected equivalent for a three-dimensional flow over a tapered pointed body is not obvious.) Any spanwise gradient in $\Gamma(y)$, $\partial\Gamma/\partial y$ must be accompanied by shedding of streamwise vorticity, and sharp changes in the gradients in $\Gamma(y)$ will be visible as variations in $w(y)$ in the near wake. Such variations in $w(y)$ can be used as diagnostics of the quality of $\Gamma(y)$.

Wing–body interference may alter the circulation at the wing root, and body circulation may exist such that the total lift of the wing–body combination may increase, as found in wind-tunnel tests of [10–14], reported by Hoerner ([4], pp. 8–17). However, such lift increment comes, necessarily, with an extra cost of lift-induced drag, due to the suboptimal spanwise variation in $\Gamma(y)$ of the combination, unless a deliberate effort is made to shape the wake. Together with additional parasite drag, the total drag of the wing–body combination is higher than that of the wing alone. Hoerner ([4], pp. 8–18) reports an increment in induced drag expressed as $\Delta C_{Db} = 0.035(\Delta C_{Lb})^2$ where the ratio of spanwise extent of the body b_b to total span b (b_b/b) ranges up to 0.2. (Here C_{Db} and C_{Lb} are based on the body-occupied planform area, cb_b.)

As proponents of BWB configurations have long noted, considerable induced drag reductions can be expected if the body geometry is designed to support, maintain, and control a nonzero circulation profile [7,15]. According to these same arguments, it also ought to be possible to provide control surfaces along the aft edge of a semistreamlined body. The pressure drag may remain significant, but streamlines do not depart very far from the outline, so that the rear stagnation point can be fixed. Furthermore, in principle, the rear stagnation line location could be made to match the condition on the wing root. In this case, to a near-wake observer, the downwash profile across the span (including the body) has little or no trace of the body. Fixing the rear stagnation line in this manner is equivalent to forcing some nonzero circulation on the body itself, which now becomes a lifting body and dynamically part of the wing. From the perspective of shedding streamwise vorticity, the vorticity shed by the body edge would have an opposite sign and approximately equal magnitude to vorticity shed from the wing root. The result will be an even $w(y)$ profile with little spanwise variation.

Described here are the initial experiments to test the hypothesis that a suitable body-circulation-control device can be deployed to modify the circulation on the body and effectively erase its inviscid signature in the wake. Although there exist a variety of concepts by which circulation control can be implemented [16,17], the detail of implementation is beyond the scope of this initial work. The device chosen for this study is referred to as a fuselage Kutta edge (KE), as it is expected to enforce the Kutta condition on the flow over the entire fuselage. A wing–body–KE combination can be shown to approach the ideal wing-alone wake quality.

III. Equipment and Methods

A. Wind Tunnel and Model

A low turbulence ($q/U \leq 0.03\%$ [18,19], where q is the root mean square of the velocity fluctuations) closed-loop wind tunnel with an octagonal test section of 1.36 m inscribed diameter was used at sea-level conditions. A rectangular, symmetric, untwisted wing with a NACA 0012 airfoil with a 76 mm chord c and 500 mm span b ($AR = 6.6$) was supported vertically at the wingtips between the top and the bottom walls of the test section. The bottom support sting was attached to a rotary table by which the geometric angle of attack α could be set to within ± 0.05 deg. The sting protruded from the lower wingtip with a diameter of 4.5 mm for the first 50 mm before tapering to the sting diameter of 8 mm. Because of this flow obstruction on the lower wingtip, the observation volume captured the top half of the model (above the plane of symmetry) where the tip support was far less obstructive. The top wingtip was supported by a pair of solid steel wires of 0.3 mm diameter splitting at 30 deg off the vertical to the sides of the top window of the test section. Model oscillations and vibrations were avoided by applying a suitable tensile prestress to these supports. The top support did not restrict the rotational degree of freedom needed to alter the model angle of attack.

A fuselage could be added to this wing in a variety of arrangements. Tests described here had the wing–body in a shoulder wing arrangement. The wing was rigged at 6 deg with fillets typical of

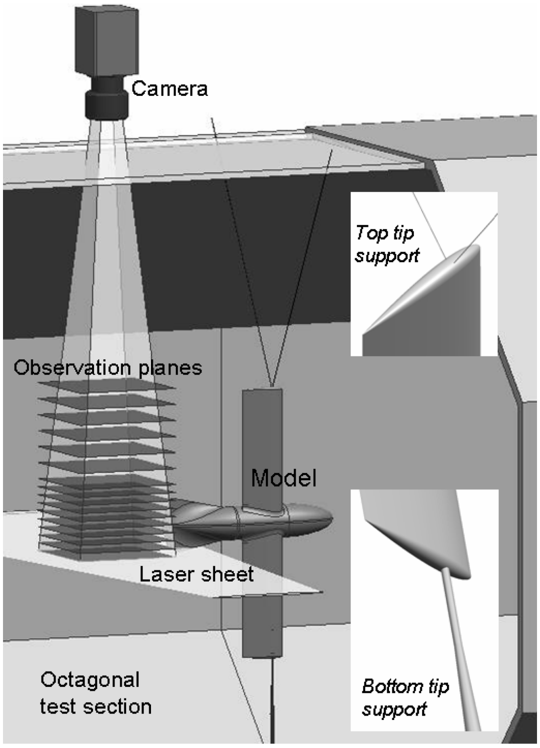


Fig. 2 The wind-tunnel model is vertically supported between a vertical sting and a pair of 0.3 mm steel wires. A vertically synchronized camera and laser sheet scan the observation volume in a smoke-seeded closed-loop wind tunnel from just below the model plane of symmetry to just beyond the upper wingtip.

the tube-and-wing arrangement. The fuselage, essentially a circular body with a diameter $d = 60$ mm, blanked off about 12% of the wing span ($d/b = b_b/b = 0.12$). The fineness ratio was $l/d = 5.5$, with a nose cone of length $1.7d$, a cylindrical section of $1.7d$, and a tail cone of $2.1d$. The tail cone could be fitted with a flat plate of any shape to provide a fuselage trailing edge. In these tests the KE had a span of 102 mm ($0.2b$) and formed a leading edge on the side of the tail cone with a sweep angle of 78 deg. This flat plate was blended with the tail cone, as visible in several figures. The aft body could be deflected to offer adjustability of the KE angle. A schematic of the experimental setup appears in Fig. 2, with details of the model shown in Fig. 3.

For optical reasons, the model was coated in nonreflective black. Matte black spray paint was applied to the wing, and the fuselage was taped over with a rough black adhesive tape. A trip wire of 0.6 mm diameter was placed on the wing upper surface at about $0.22c$ and around the fuselage at the wing trailing edge ahead of the tail cone, the pressure recovery region of the fuselage. These measures were taken in an attempt to force flow transition in the low-Reynolds-number boundary layer to improve the conditions for the flow to remain attached or to reattach.

B. Flow Visualization Setup

A dual-head Nd:YAG laser emitting a pair of coaxial laser beams was used to illuminate oil-based smoke in a horizontal sheet about 4 mm thick behind the vertically mounted model. A dual-frame Kodak ES4.0 CCD camera captured a pair of square images at a resolution of 1024×1024 pixels, exposed for less than 5 ns each with typically 180 μs between the two laser shots. With an 85 mm 1:10 Nikon lens positioned 1.3 m from the observation plane, the square observation frame captured 192×192 mm, and the freestream displacement ($U = 10$ m/s) had a mean pixel displace-

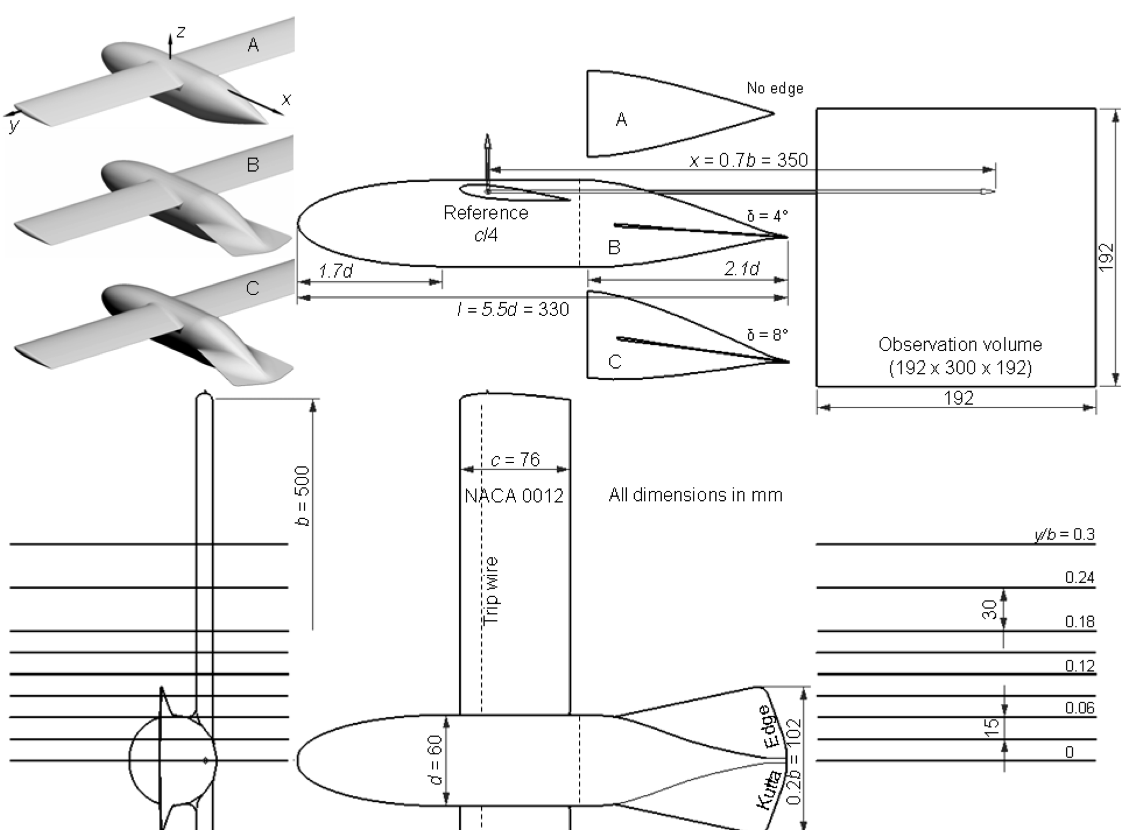


Fig. 3 After testing only the rectangular wing, a body was added rigged at 6 deg in the shoulder-wing arrangement. After testing the combination with the pointed fuselage without a trailing edge (A), a KE was added. Then the tail cone was deflected down by 4 deg (B) and later to $\delta = 8$ deg (C). The observation planes used in this report are shown here to scale in their relative positions. Streamwise averages were derived around $x = 0.7b$ behind the reference point.

ment of approximately 9.6 pixels. Fifty frame pairs were taken at a rate of 4.8 Hz at each test station. Synchronized vertical traversing of the camera and the laser sheet provided the means for the spanwise scan of the observation volume.

C. Test Matrix

Initial tests were conducted with the wing alone. This provided the baseline for comparisons with wing–body geometries illustrated in Fig. 3. The fuselage without a KE was then added to the wing (model A in Fig. 3). For the reference tests described here, the fuselage axis was parallel to the freestream flow, thus giving a wing angle of attack $\alpha = 6$ deg.

For the next series of tests the KE was added to the fuselage tail cone. Three different KE incidence angles were tested, $\delta = 0$, 4, and 8 deg down from the freestream axis. The latter two are models B and C in Fig. 3, respectively. The $\delta = 0$ deg case provided confirmation that the KE did in fact alter the flowfield, but in an undesirable way. The $\delta = 4$ deg case had the KE at an angle slightly less than that of the wing (rigged at 6 deg), whereas $\delta = 8$ deg held it at slightly more. It was anticipated that the two cases would demonstrate a useful trend in wake modification.

Every test commenced with the wing angle of attack $\alpha = 0$ deg (thus with the body axis at -6 deg), with the first observation plane three stations below the model plane of symmetry. After acquiring 50 frame pairs, the spanwise position of the observation frame was changed until reaching the last station beyond the wingtip. The angle of attack was then increased by 2 deg and the spanwise scan was repeated in reverse. This was repeated until $\alpha = 8$ deg. In this way all five cases (wing-only, no edge, and $\delta = 0$, 4, and 8 deg) were tested under the same test conditions.

D. Processing

A customized variant of the correlation imaging velocimetry (CIV) algorithms of [20] was used to estimate the displacement field from each frame pair. A most-likely cross-correlation function is estimated by fitting an average of two spline-interpolated autocorrelation functions calculated from the same correlation subwindows in the two images of each pair. The range of possible displacements of a correlation window is completely separated from the window dimensions itself, and arbitrary shifts can be added or subtracted to take into account mean background flows. The bandwidth of the correlation displacements is thus optimized about the disturbance velocity field and not for the mean. Estimated displacements were moved to a location halfway along the displacement vector, and were then reinterpolated onto a regular grid of 65×66 grid points, using the two-dimensional spline-interpolation algorithms described by Spedding and Rignot [21].

During postprocessing, the true mean freestream velocity U, as derived from the observed flowfield, was subtracted from each $\{U + u, w\}(x, z)$ field to yield the disturbance flowfield $\{u, w\}(x, z)$ as induced by the model. Images aligned with the vertical aircraft axis z and parallel to U give the disturbance velocity components u and w in x and z. Each of the 50 $\{u, w\}$ field estimates was inspected in its 4290 grid points, and obvious flaws were removed before calculating the time average over the 10.4 s period to yield the time averaged disturbance flowfields $\{\bar{u}, \bar{w}\}(x, z)$. The multiple planes in the spanwise direction y of $\{\bar{u}, \bar{w}\}(x, z)$ formed the basis for subsequent analysis.

The data from these observation frames were then assembled into three-dimensional data sets for import into the flow visualization tool ParaView. By visualizing the entire flowfield in the observation volume, a qualitative but global understanding could be obtained as to how the various model changes affected the wake. This provided the focus and context for more selected quantitative comparisons. Of the five test cases the $\delta = 0$ deg case is not included in the description of the data in this report. Of the five tested angles of attack only the 6 deg reference case is used here as representative of an aircraft in a steady cruise condition with the body aligned with the flow. Of the 15 spanwise stations, the outer stations, which appeared to be beyond the influence of the body and the KE, have been excluded from this report.

IV. Limits and Accuracy

A. Experimental Limitations

The purpose of this investigation was to distil the equivalent of the simplified schematic presentation of Fig. 1 from actual experimental data and then to test the influence on such downwash distributions by the addition and manipulation of the fuselage trailing edge. Although it was to be determined whether the cause of wake deterioration of a wing–body combination could in principle be removed by means of fuselage trailing edge manipulations, no attempts were made to precisely remove this cause or even to quantify the changes in drag. Useful drag measurements are difficult to obtain, and here only small changes to induced drag are expected, which, at this scale, are overwhelmed by complex viscous issues. Similarly, it was reasoned that little could be gained to verify predictions from measurement of lift. Force measurements were taken for preparatory purposes alone and therefore are not included in this discussion.

1. Observation Volume

The schematic representation of Fig. 1b qualitatively shows an effect in the inviscid field as induced by the complex flow interactions with an air vehicle. Although it is sufficient to observe the induced effect in the inviscid disturbance field to discover departure from or return to the ideal wake of Fig. 1a, it is useful to understand the cause of such changes. The affected field is huge and the measurable disturbance varies considerably with relative location to the model. In comparison to the inviscid disturbance field, the viscid disturbance is limited to a very small portion of the affected field trailing from the solid boundaries of the model. Because the disturbance of shed vorticity approximately coincides with this viscous wake, flow observations had to include this region. However, the key observations come only from the inviscid disturbance field above and below the viscous wake (see Fig. 4).

A spanwise stack of longitudinal frames formed the observation volume, as illustrated in Fig. 2. In this orientation, the entire optic array could be mounted rigidly and free from any contact with the wind tunnel. None of the equipment was exposed to the airflow, and the flowfield was completely unobstructed. However, in this arrangement the spanwise component v was unobservable and only the velocity components $\{u, w\}$ in streamwise (x, z) planes could be estimated. These components are in the direction of drag and lift, respectively. The streamwise vorticity, $\omega_x = \partial w/\partial y - \partial v/\partial z$, was therefore also unknown. The local magnitude of $\partial w/\partial y$ could not be reliably estimated from the coarse discretization in y (also the $\partial v/\partial z$ component was unavailable), and so the focus was exclusively on the larger scale spanwise variation $w(y)$ where the time-averaged distribution was measured reliably and repeatably through the multiple spanwise slices.

Comparative investigations could be performed from the estimated disturbance vectors in some 64,000 grid points within the total observation volume. Although this yielded high-density information, the total volume is small in comparison to the volume of flow affected by the model. It was therefore not feasible to derive the global magnitudes of the influence under investigation. However, comparative tests were on an equal basis.

2. Low Reynolds Number

With the freestream velocity $U = 10$ m/s over the chord $c = 76$ mm and with ν the kinematic viscosity, the $Re = Uc/\nu$ was on the order of 45,000. Model and tunnel size, model support considerations and smoke seeding limitations restricted data collection to this low Re. Because the basic arguments are made in the usual aeronautical context in which Re is assumed to be large, certain special precautions were taken to ensure that the test objectives could be achieved.

The global disturbance field reflects the influence induced by the pressure field around the model, whereas only a small fraction of the

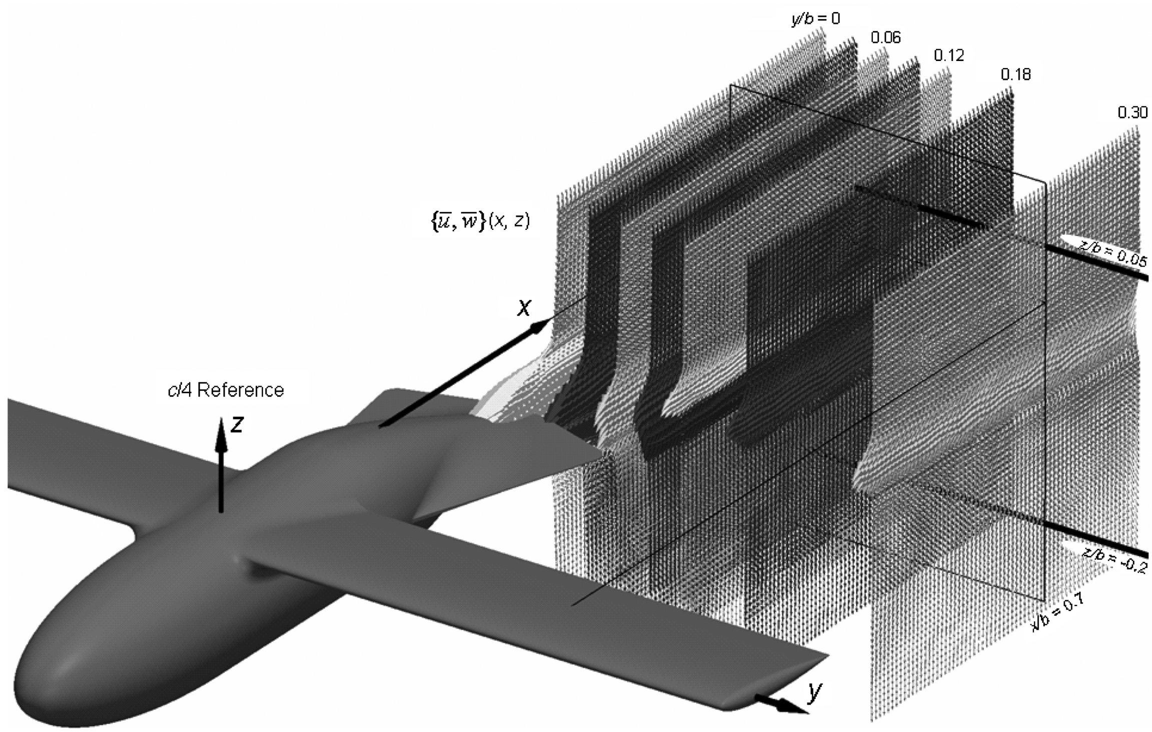


Fig. 4 Flow vectors were estimated in 65 × 66 (4290) grid points in each of 15 (x, z) observation planes (of which seven are shown here). Removal of the freestream velocity from time-averaged estimates yielded the disturbance fields $\{\bar{u}, \bar{w}\}(x, z)$ in which the viscous wake is here clearly visible just below the reference z plane. Spanwise downwash distributions of Figs. 6 and 8 were derived from streamwise averages take around $x = 0.7b$ in the vertical locations shown above and below the viscous wake.

wake shows the traces of the viscous interactions with the model. Therefore, the proposed phenomena should be observable in the global disturbance field if the pressure field is representative of that of a typical full-scale aircraft in subsonic flight. Furthermore, as long as the Kutta condition holds on all relevant trailing edges (implying that the rear stagnation remains on the relevant trailing edge), even in the presence of separation, the circulation should be representative of a field in which separation is absent. Therefore, a range of wing angles of attack was chosen ($\alpha = 0$ to 8 deg), at which reasonable wing circulation prevailed. During preparatory experiments lift measurements were used to establish the lift curves for the wing-only case. Combined with CIV observations on the wing upper surface, the absence of problematic flow separation on the wing could be confirmed.

The same could not be done for the fuselage because the circular cross-section and awkward optical reflections obscured the boundary-layer regions from CIV images. It therefore had to be assumed that flow separation was likely to prevail in the pressure recovery region of the fuselage, just behind the wing trailing edge, given the low *Re*. However, if the fuselage is observed to affect the circulation in the central region of the wing–body arrangement, it would be hard to explain how the absence of separation could leave wing circulation intact. Furthermore, the downwash defect of wing–body arrangements at high *Re* has been observed by others (e.g., Jacobs and Ward [10]). After adding the KE and deflecting the aft body down, flow separation could become even more problematic, but again, the absence of separation would be in favor of the phenomena to be observed. If the phenomenon is observable in the presence of separation at low *Re*, then it should be reasonable to assume that it will be observable under more favorable conditions in the absence of separation at any higher *Re*.

3. *Averaging*

Flow at such a low *Re* is unsteady in the viscous wake (as shown by Spedding and McArthur [22]), but quantitative measurements can be derived from suitable time and space averages [23]. Extensive preparatory work was done to select appropriate setup parameters and to choose a proper observation volume size and location. This work was primarily conducted on the wing-only case and also involved force measurements. Here each spanwise observation was made in four streamwise stations starting on the wing itself. For higher data density, a smaller observation frame was used, given the smaller obstruction in the flow. Angle-of-attack sweeps of larger range and smaller increments were used to observe separation patterns on the wing and to observe their streamwise trails. Sensitivity studies were conducted to find an appropriate number of observations n as a basis for time averaging. Results presented here used $n = 50$ frame pairs. This showed convergence of the downwash statistics well within this data length for various separation patterns. Even in the unsteady wake of separation, convergence of disturbance magnitudes was reached within $n = 30$, and in outer wake regions convergence had already been reached with $n = 10$. Here $\bar{w}$ is the time average of the downwash w in each grid point.

Time-averaged data were further smoothed by space averaging over a streamwise portion, Δx. Initial investigations showed that the measurement of vertical downwash profiles was insensitive to the streamwise location, provided that a consistent location was used for the comparisons. Therefore the last of the four streamwise stations of the wing-only case was used for all further observations. Cases that included the body required a larger observation frame clear of the body and the KE. Streamwise data averaging was performed in the overlapping portion of the different observation frames, and so it was done around $x = 0.7b$ (downstream of the quarter chord, $c/4$, reference of the wing) over a streamwise portion of $\Delta x = 0.2b$, as illustrated in Fig. 5. Then $\langle \bar{w} \rangle$ is the streamwise space average over Δx of the time average of w taken from 50 estimates over a period of 10.4 s at a rate of 4.8 Hz.

B. Experimental Accuracy and Reliability

In a well-designed experiment, CIV-based estimates of the in-plane velocity components can be resolved to within 5% of their true value, and uncertainties in estimation of spatial gradients can be within 10% [20]. No explicit use of gradient quantities is made here, and all the data are obtained exclusively from time averages. Thus,

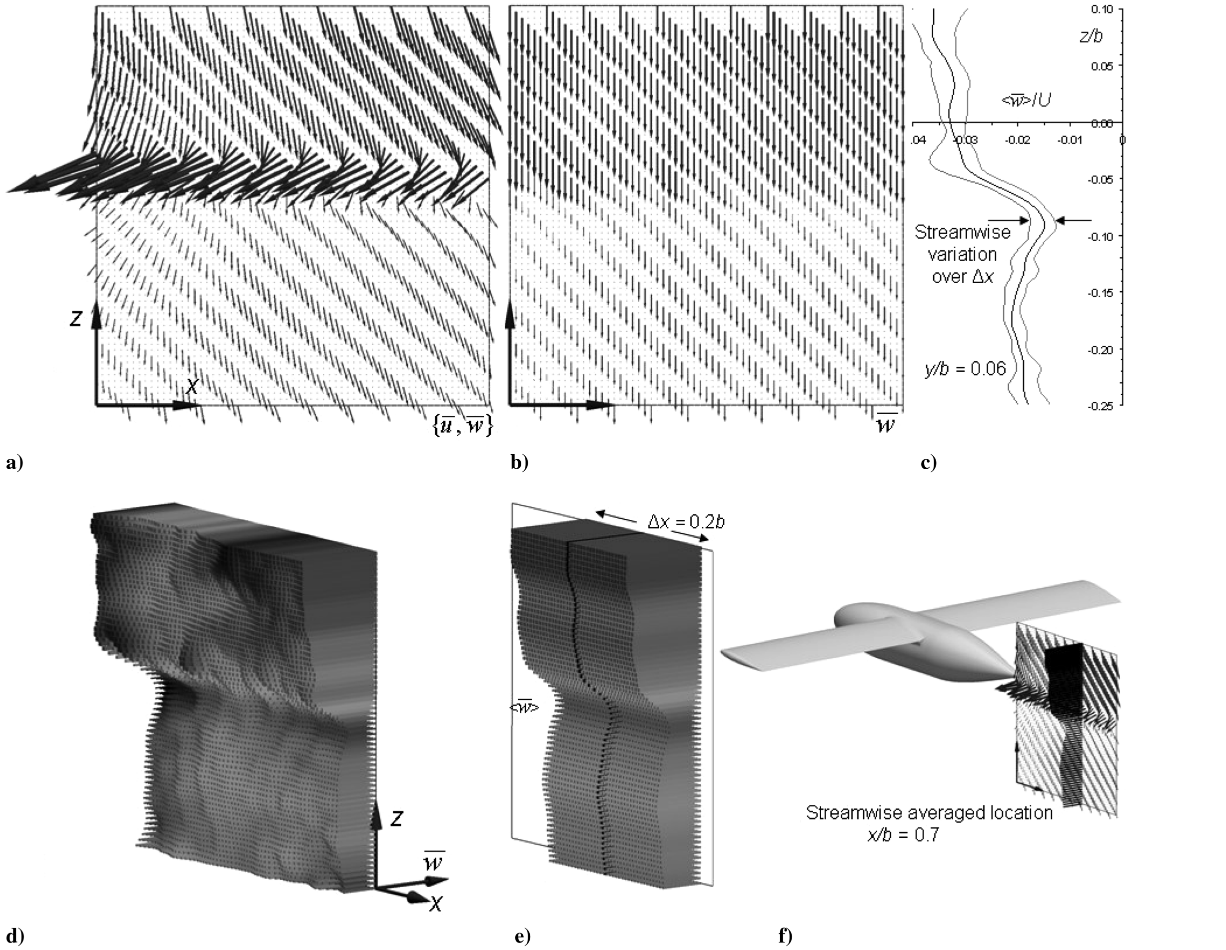


Fig. 5 From the time-averaged disturbance velocity field $\{\bar{u}, \bar{w}\}(x, z)$ in a) the downwash, $\bar{w}(x, z)$ is isolated, shown as a vector field in b) and again as a surface in d) (formed by perpendicular bars of downwash magnitude). Residual fluctuations in $\bar{w}$ are removed in e) by streamwise averaging over the illustrated portion of data (Δx). The resulting mean vertical downwash profile $\langle\bar{w}\rangle(z)$ is quantified in c) between the bands of maximum and minimum values within Δx. The relative position to the model is shown in f).

the level of confidence with which to evaluate the data may be indirectly assessed, as any single observation made at every single grid point over a period of time is acquired in complete independence of any other. Therefore, the relative similarity of such observations, both in terms of neighbors as well as post- and predecessors, offers a measure of confidence in the reliability of the observation.

The absolute accuracy depends on numerous aspects of the experimental setup and procedures. Proper control over lighting uniformity, particle seeding density, image brightness, and freestream uniformity are all critical components that are necessary for the claimed uncertainties [24]. In addition, there are certain systematic deviations from ideal geometry, involving optical distortions and small uncertainties in light-plane orientation, that degrade the absolute accuracy. However, in comparative measures of time-averaged velocities, the time-averaged data can be reliable to within 1% [20].

In comparative measures of time-averaged velocities, repeated measurements (from different days) of mean flow and peak defect velocities were within $\pm 1\%$ of each other. The same measurement setup has been shown to yield flat plate drag coefficients to within 5% of their theoretical value from interrogation of mean defect profiles, and mean flow quantities are checked against those derived from pitot static tube measurements each day.

V. Results

A. Data Reduction Sequence

Figure 5 shows, by means of one sample observation, the data reduction sequence that provides the basis for the comparative wake survey. Figure 5a shows a typical vector map $\{\bar{u}, \bar{w}\}$ of a disturbance field in the (x, z) plane, as derived by removing the mean freestream velocity component U and time averaging over 50 CIV estimates in each of the 4290 grid points (of which only every sixth vector is shown in Figs. 5a and 5b). Figure 5b shows the isolated downwash component $\bar{w}$ after removal of the $\bar{u}$ component, which previously made the viscous wake of the wing and body clearly visible.

In Fig. 5d the downwash field $\bar{w}(x, z)$ is again displayed, now as a surface formed by perpendicular bars of downwash strength in each grid point. Small-amplitude residual fluctuations are noticeable close to the body, but those farther downstream are negligible, and in Fig. 5e, these have been removed by averaging over a cropped portion of the data in only the streamwise direction x as described previously.

The resulting streamwise-averaged vertical downwash profile $\langle\bar{w}\rangle(z)$ is repeated in nondimensional form, $\langle\bar{w}\rangle/U$ against z/b, in Fig. 5c. Here the inner line shows the streamwise average $\langle\bar{w}\rangle$ and the bounding lines show the limits of streamwise variation of $\bar{w}/U(z)$ over the averaged portion of the data. The vertical reference in Fig. 5c coincides with the $c/4$ reference of the wing. The relative position of the sample observation frame is shown in Fig. 5f. Its spanwise location is at $y/b = 0.06$, a vertical plane tangent to the side of the round fuselage without a KE.

Such streamwise-averaged profiles of $\langle\bar{w}\rangle(z)$ will be compared for the four different configurations: wing-only, wing with body (no edge), and body with KE at $\delta = 4$ and $\delta = 8$ deg. Henceforth, only the time- and space-averaged downwash $\langle\bar{w}\rangle$ will be considered, but the overbar and the brackets will be dropped for simplicity. In Fig. 6 such average vertical downwash distributions are displayed in their respective spanwise positions for the different test cases.

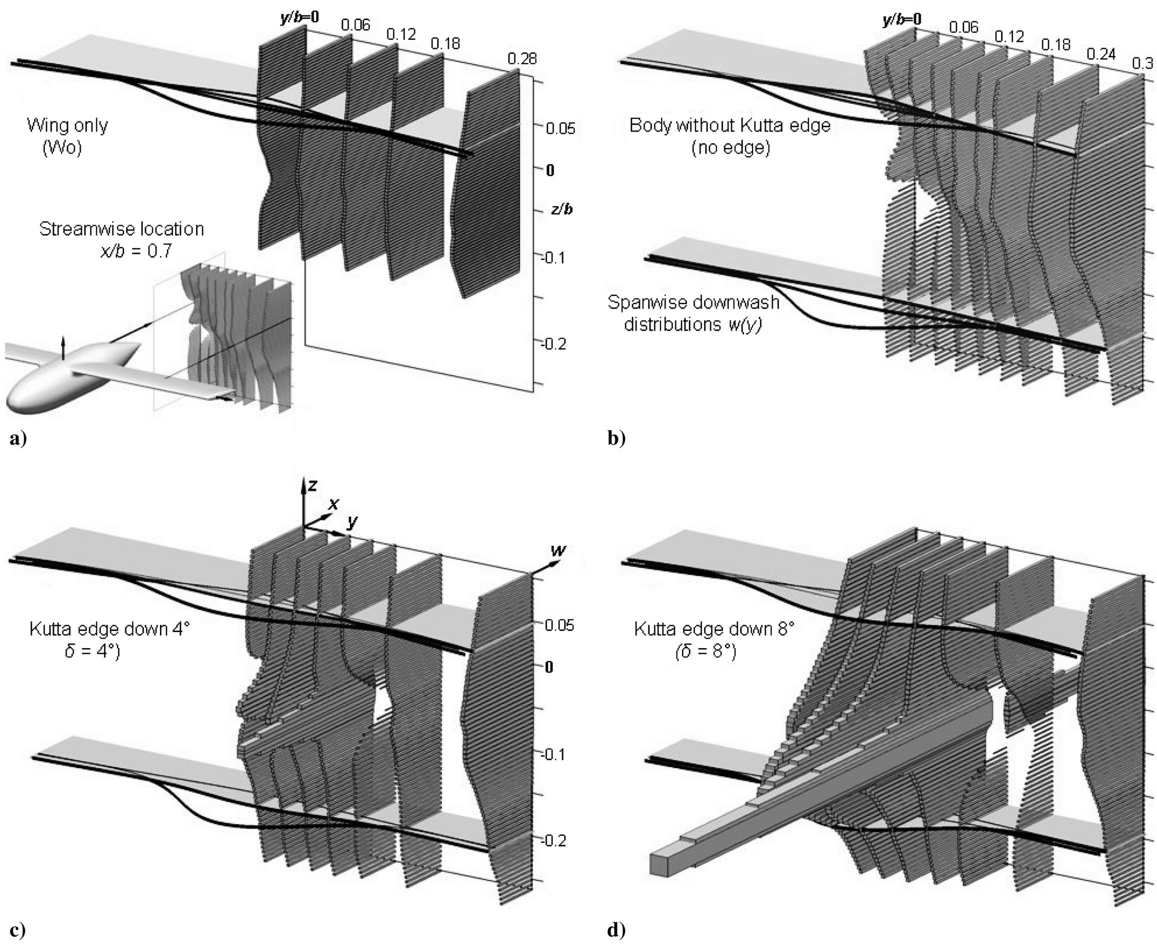


Fig. 6 Vertical downwash profiles (as derived in the previous figure) have been assembled at their spanwise locations to show the complex downwash landscapes in the (y, z) plane for the four test cases. (Note, the bars of downwash magnitude are now aligned with the x axis, with upwash being positive.) Ribbons of spanwise downwash distributions $w(y)$ are shown at two vertical locations, $z/b = 0.05$ and -0.2 (above and below the viscous wake region). These are mirrored across the plane of symmetry and all are superimposed in each landscape for comparison. These ribbons are repeated, more appropriately orientated in Fig. 8. The insert shows the downwash landscape in its relative position (comparable to Fig. 4).

B. Effect of Fuselage with Trailing Edge on Near Wake

A summary and sample of the effect of the fuselage and the KE on the wake is given in Fig. 6, which is arranged to show how representative spanwise downwash profiles alone can eventually be used to compare with the simplified prediction of Fig. 1.

The vertical downwash profiles, as described in Fig. 5, are assembled in their relative positions along the span to illustrate the downwash landscape in a (y, z) plane in $x/b = 0.7$ downstream of the $c/4$ point of the wing. Again perpendicular bars show the magnitude of downwash (with bars in the direction of x representing upwash). The downwash profiles of the wing-only at $\alpha = 6$ deg (Fig. 6a) are quite uniform along the span y and in the vertical direction z. There is no evidence of any inner trailing vortex cores (given the absence of any up- and downwash peaks that would otherwise be expected close to a vortex core).

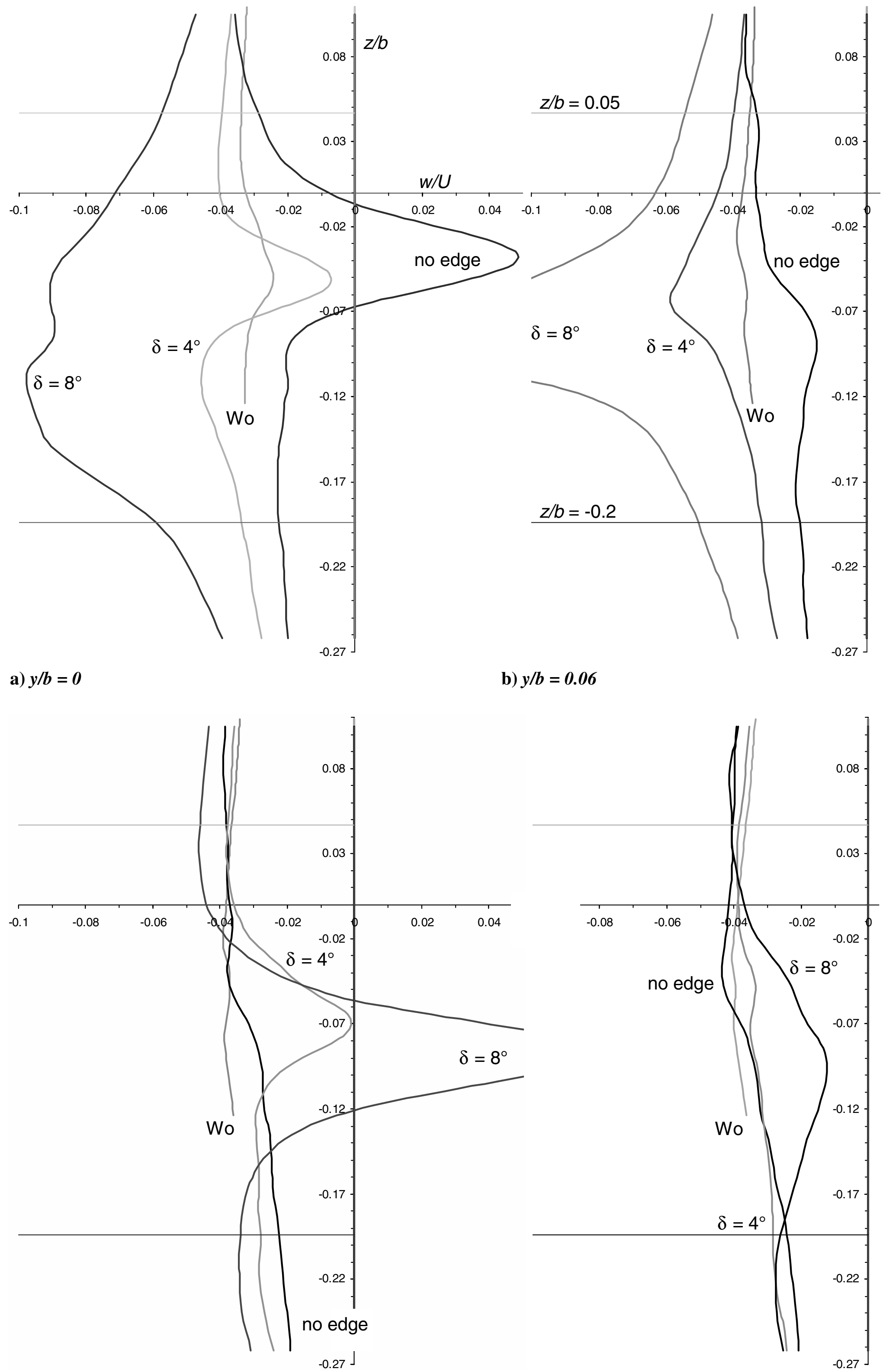
A slight reduction in downwash due to viscous momentum transfer by the wing is visible in each vertical profile. This defect indicates the vertical location of the viscous wake, washed down slightly below the reference plane at $z/b = 0$. (The larger deficiency in the central plane is found in the disturbance trail caused by exposed fuselage mounting holes in the center of the wing.) The slight increase in downwash toward the tips is to be expected from a rectangular untwisted wing (unlike the constant spanwise downwash of the untwisted elliptical wing of Fig. 1a). Also the almost symmetrical reduction in downwash in the vertical profiles, when departing from the vertical location of the viscous wake, is in line with expectations.

When the body without the KE is added to the wing (Fig. 6b), a prominent upwash peak appears in the central plane (clearly visible in Fig. 7a) together with a downwash peak in the neighboring plane (at $y/b = 0.03$). This is consistent with the presence of a trailing vortex core somewhere between these planes. This is in line with the expectation that the Kutta condition will break down due to the discontinuity in the initial vortex sheet in the portion of the wing now occupied by the fuselage.

It appears that this central trailing vortex pair induces the downwash deficiency observable in the lower portion of the central wake as far out as $y/b = 0.12$. Although downwash above the wing is not affected by much (a slight decrease in the central region and even an increase toward the wingtips), the near vertical symmetry of the wingonly case has been lost with a downwash deficiency clearly visible in the lower portion of the distorted landscape of Fig. 6b. This distortion/variation in $w(y, z)$ will inevitably come with an induced drag penalty when compared to a wing-only case on the basis of equal lift. These observations are consistent with predictions of Fig. 1, and are quite consistent with classical data reported by Hoerner and Borst ([3], pp. 20–14) and Hoerner ([4], pp. 8–16]).

Figures 6c and 6d show the same wing-fuselage combination after the KE has been added and deflected downward by $\delta = 4$ and $\delta = 8$ deg, respectively. The spanwise downwash defect caused by the pointed body in Fig. 6b has been largely removed in Fig. 6c, and the central downwash is even increased slightly. The higher KE deflection in Fig. 6d produces a strong increase in central downwash, and now the wing–body–tail combination is increasing the total lift.

A careful tuning of deflection angle, δ, and tail shape and size is beyond the scope of this initial study, but the near-restoration of normal downwash profiles by $y/b = 0.18$ for the $\delta = 4$ deg case shows that the flow has been returned close to the condition of the wing alone, and the inviscid body wake signature has almost been removed. The removal of the adverse influence of the body on the wake, and its commensurate reduction in the induced drag penalty, can be considered either from the point of view of evening out the $w(y)$ wake profile, or of a change in wing–body–tail $\Gamma(y)$ distribution so that trailing vortices shed by the positively loaded body–tail exactly cancel out the wing root vortices of opposite sign.



a) *y/b = 0* b) *y/b = 0.06* c) *y/b = 0.12* d) *y/b = 0.18*

Fig. 7 Vertical downwash profiles $w(z)$ of the four cases are shown superimposed at various spanwise locations. The KE tip is located between $y/b = 0.06$ and 0.12 (visible in Figs. 3 and 8), and the peaks in the profiles of opposing direction in b) and c) for the cases with the KE are consistent with the presence of trailing vortices of different strength. The upwash peak in the plane of symmetry reveals a trailing vortex of opposite direction behind the fuselage without the edge. In the core region between the vertical limits shown, high local downwash intensities are found close to the trailing vortex cores. Therefore, the downwash distributions of the previous and the next figure have been derived outside this core region.

In either formulation, for the ideal case a downwash survey behind the aircraft will find no evidence of any inner vortex cores or of the body itself.

Each panel in Fig. 6 also repeats the progressive reconstruction of spanwise downwash distributions $w(y)$ as shown by the superimposed ribbons in two different vertical locations. The top location ($z/b = 0.05$ above the vertical reference) and the lower location ($z/b = -0.2$) have been chosen close to (but beyond) the viscous wake region. Profiles extracted any closer to the vortex cores would show strong distortions due to the intense local disturbances. From Fig. 7 it can be derived that profiles from farther beyond this region would qualitatively show the same trend. These profiles provide the experimental equivalent of the schematic predictions of Fig. 1.

For comparison, Fig. 7 superimposes the vertical downwash profiles $w(z)$ of the four cases at four different spanwise locations. At $y/b = 0$ (Fig. 7a), the strong upwash peak described previously is visible for the case of the fuselage without the KE (no edge). By contrast, the case with the KE fully down ($\delta = 8$ deg) shows very strong downwash in the central plane, whereas the case with the KE halfway down ($\delta = 4$ deg) is intermediate between the two and compares more closely with the wing-only case. When going from about halfway to the KE tip ($y/b = 0.06$, Fig. 7b) to just beyond the KE tip ($y/b = 0.12$, Fig. 7c), local downwash peaks turn to opposite peaks. It follows that these longitudinal planes lie on either side of a trailing vortex core shed from the lifting body–tail combination. The peak intensity is much smaller for the $\delta = 4$ deg case, suggesting than an even smaller deflection may yield a wake without such peaks and thus without a central trailing vortex core.

Farther out, from $y/b = 0.18$ (Fig. 7d), the downwash begins to converge and the influence of the fuselage with or without the KE has almost disappeared. It should be noted that this is well beyond the lateral extent of the fuselage ($y/b = 0.03$), even well beyond the span of the KE ($y/b = 0.1$). The two vertical locations ($z/b = 0.05$ and -0.2) from which the spanwise distribution profiles of Figs. 6 and 8 were derived are also indicated in Fig. 7.

C. Control of Wing–Body Circulation with a Kutta Edge

Figure 8 summarizes the effect of a deflected KE on the wing–body–tail wake and represents the experimental equivalent to Fig. 1. The upper downwash distributions include the wing-only case, and it can be seen that the addition of the body without the KE (no edge) reduces the central downwash, as predicted in Fig. 1b. Deflecting the KE to $\delta = 4$ deg restores the downwash profile close to the original, wing-only condition. When $\delta = 8$ deg, the tail becomes a high-lift device and the central downwash is increased significantly. If the $\delta = 4$ deg configuration is described as a return to an effective wing-only condition, then the $\delta = 8$ deg case is analogous to a high-lift device such as a trailing edge flap.

VI. Discussion

A. Implementation of a Fuselage Kutta Edge

The experiment confirmed that manipulations of the KE have a profound effect on the wake structure, and it appears possible, in principle, to find KE configurations in which any nonviscous downwash deficiency caused by a fuselage can be corrected to improve span efficiency. Success would be confirmed here by uniform spanwise downwash and/or absence of traces of inner streamwise vortex cores. The KE can also be used as part of a high-lift device. With appropriate matching to the wing circulation, any adverse wing root trailing vortices may be cancelled by an appropriately configured KE. It will be the responsibility of the designer to implement such strategies compatible with stability and balance requirements.

It would be useful to study the movement of the center of pressure in response to body edge modifications and changes in angle of attack. Insight into the influence on the aircraft neutral point by such a body edge would be equally useful.

Although significant further research will be required before the KE can be implemented as a practical method to control wake quality, these features appear to be well established and consistently implemented in the natural flight of birds, and possibly bats too.

B. Potential Consequences of Implementation

Assuming that pitch trim can be obtained by other means [8], it is conceivable to use a fuselage KE to control wake quality in order to maintain the highest possible span efficiency during all flight conditions. Additionally, as a dynamic part of a high-lift system, such a facility can significantly improve wing effectiveness. When used appropriately in conjunction with a high-lift device on the wing, a constant spanwise distribution of stronger downwash may be maintained with the help of a fuselage trailing edge. Downwash behind the fuselage implies that the fuselage contributes, as a result of a favorable pressure distribution, to the total aircraft lift. Such lift would not come from the edge feature alone but from the entire body, of which the forward stagnation line is controlled by the KE. This will permit a reduction in wing size for a given design objective. This may be significant for wide bodies (large b_b/b) of reduced fineness ratio and should easily offset any additional wetted surface required to form the trailing edge feature. Together with

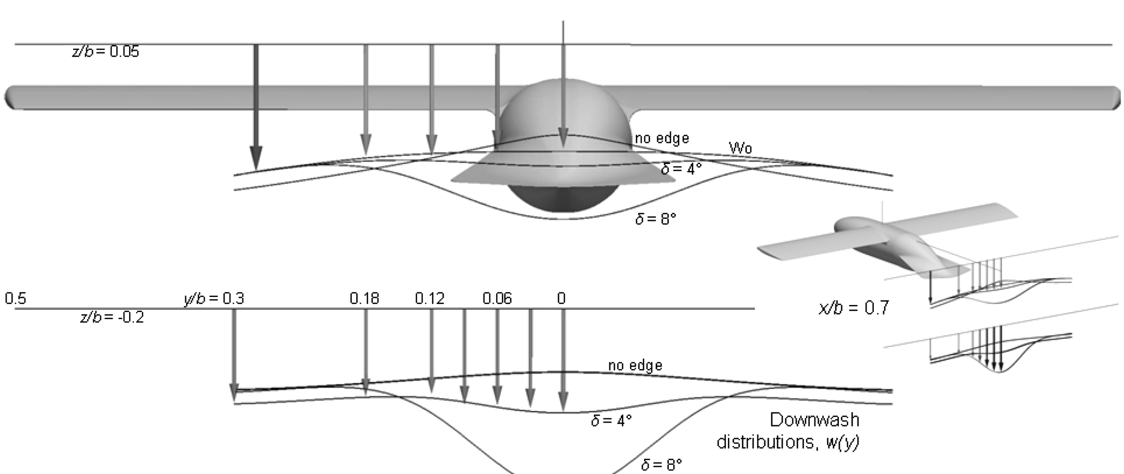


Fig. 8 The spanwise downwash distributions $w(y)$ of Fig. 6 are repeated here in their two vertical locations for the different test cases. This is the experimental equivalent of the schematic representation of Fig. 1. Note how far the influence on the downwash distribution by the body (with or without edge) extends along the span.

improved wing-bending moments, the preceding factors combine to reduce aircraft mass and wetted surface, resulting in improved aerodynamic efficiency.

If the adverse effect of the fuselage can be eliminated as proposed, the aircraft designer may employ a fuselage much wider than commonly used, and fineness ratios can be decreased toward the subsonic optimum of 3:6 (Hoerner [4], pp. 6–19, and McCormick [9], Chap. 4, p. 165). Nothing prohibits the retention of an elliptical fuselage cross-section to avoid compromising structural efficiency related to pressurization or volumetric efficiency for accommodating payload. The fuselage of smaller fineness ratio can often accommodate the same payload in a smaller total volume, depending on payload grain size. This has positive implications for both wetted surface and structural mass. The tube-and-wing configuration can be retained to benefit from its general suitability, and elaborate wing–body blending will not be required.

Finally, a fuselage fitted with such a body edge has been shown to be statically stable, as demonstrated by many applications in air and water. This reduces the responsibility of other features to provide such stability for the fuselage.

The preceding implies that the implementation of a well-designed circulation control system can make direct and indirect contributions to aircraft efficiency in several distinct ways:

1) The wing becomes more effective and it can therefore be smaller and lighter, with less wetted area.

2) The fuselage contribution to lift reduces the wing size and bending moments resulting in a smaller and lighter wing, with less wetted area.

3) The fineness ratio of the fuselage can be optimized to reduce fuselage wetted area.

4) The total fuselage volume can be reduced in favor of a lighter fuselage with less wetted area.

5) The wake quality can be improved for a better span efficiency.

6) The statically stable fuselage reduces the demand on other stabilizing features.

Taken together, the potential exists for a higher efficiency limit, allowing improvement of the mass ratio of the payload to carrier mass, the total wetted surface, and the wake quality beyond that possible using the current design approach. This is the basis for the speculation that a hypothetical ideal aircraft configuration will include a feature comparable in function and effect to the described fuselage KE.

VII. Conclusions

The experiment confirmed that the addition of a fuselage to a wing induces an adverse distortion of the wake, which, on the basis of equal lift, inevitably introduces a penalty in induced drag. Adverse inner trailing vortices have been suspected as the cause of wake deterioration. Convincing evidence of such vortices has been observed in the correlation imaging velocimetry data.

Furthermore, the experiment confirmed that the addition of a fuselage trailing edge has a profound effect on the wake, even well beyond its own spanwise extent. The wake pattern does indeed respond prominently to manipulations of the fuselage Kutta edge (KE). Such manipulations strongly affect the location and strength of inner trailing vortices and allow for their direction to be reversed. This allows the speculation that an appropriate KE arrangement can be provided by which adverse inner trailing vortices can be avoided altogether when adding a fuselage of typical shape to a wing. Thus, span efficiency does not need to be compromised by a practical fuselage.

The experiment also confirmed that total downwash can be increased significantly by means of the fuselage KE, again beyond its own spanwise extent. This allows the speculation that a KE could be a useful part of a high-lift system.

Besides the speculation that the implementation of a well-designed circulation-control device will offer several secondary benefits, it is concluded that flight with an ideal wake should be possible for wing–body aircraft configurations. The fuselage KE may be the key feature in such an achievement.

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AIRCRAFT

FIELD OF THE INVENTION

This invention relates to an aircraft. It further relates to a method of controlling an aircraft in flight.

BACKGROUND OF THE INVENTION

All the energy of flight is transferred from a flight body to the surrounding viscous medium through which the flight body is moving as the shear forces and pressure interactions between the flight body and the viscous medium change the momentum and the temperature of the medium. It is in the interest of any operator of any flight to transfer only the minimum amount of energy to the surrounding medium for the sake of good flight economy. Accordingly, in the interests of efficiency, some design qualities which should be concurrently minimized during the process of flight body design include:

The flight body should be minimized in terms of its requirement for lift;

It should be minimized in terms of its transfer of momentum by shear and pressure forces to the surrounding viscous medium; and

It should shed the minimum kinetic energy for the change of momentum required to produce lift.

Aircraft of the current art of which the Inventor is aware do not fully achieve any of these three objectives and therefore consume more energy during flight than would be physically necessary to achieve a given flight objective. It is an object of this invention to provide means which the Inventor believes will at least ameliorate some of the inefficiencies associated with the prior art.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided an aircraft which includes:

a tailless fuselage which has a body which includes a transverse trailing edge, the body having a fineness ratio of between 3 and 7; and

a wing having two sides which protrude from opposite sides of the fuselage.

The fineness ratio may be 4.5.

In the context of this specification the term "tailless fuselage" is to be understood as a fuselage without an empennage and in particular which does not have a vertical stabiliser at the rear of the fuselage and which does not have a rearward fuselage extension specifically for the purpose of holding the empennage.

The aircraft may include a power source for propelling the aircraft.

The trailing edge of the fuselage may be adjustable. The body may include a bulbous primary section and a flap which is connected to the primary section and which forms the trailing edge. The flap may be displaceable relative to the primary section to permit adjustment of the trailing edge. The flap may be displaceable relative to the primary section about a transverse axis. In particular, the flap may be displaceable upwardly, relative to a neutral position, by up to 30° and downwardly relative to the neutral position, by up to 60°. The neutral position is the position the flap would occupy during steady state horizontal flight at cruising velocity.

In the context of this specification, the Fineness Ratio will be understood to be the Body Length / Effective Diameter.

The Body Length is the distance from the nose to the end of the primary section of the body (thus the extension of the body by the flap would not be included in the Body Length).

The Effective Diameter for a round body would be its maximum diameter, and for a non-round body would be the square root of its maximum width times its maximum height.

The width of the trailing edge may be adjustable. The flap may include a plurality of transversely spaced sections which are laterally displaceable relative to one another in order to increase or decrease the width of the trailing edge. The width of the flap at the trailing edge may be adjustable between 0.5 and 3 times the maximum width of the primary section of the body.

The longitudinal positon of the trailing edge may be adjustable. To this end, the effective length of the flap may be adjustable.

Each side of the wing may have an inner section which is inclined upwardly away from the body and an outer section which is inclined downwardly. At least a portion of each side of the wing may be swept back. The inner section of each side of the wing may be swept forward with a positive dihedral and the outer section of each side of the wing may be swept back with a negative dihedral or anhedral. With sweep angles typically defined on a quarter chord line of the wing, the inner wing sweep angle, i.e. the sweep angle of the inner portion of each side of the wing, may be approximately 5° forward and the outer wing sweep angle, i.e. the sweep angle of the outer portion of each side of the wing, may be approximately 25° backward. Inner wing dihedral of each side of the wing may be approximately 3° and outer wing anhedral of each side of the wing may be approximately 5° for a wing arranged in a shoulder wing position.

One disadvantage of a wing optimised for flight efficiency is that it typically has insufficient volume or internal height in order to accommodate a payload or other large elements. Therefore, a fuselage has to be provided. The fuselage may have a volume which is typically approximately four times the volume of the wings. Typically, the fuselage or body in accordance with the invention will be designed to be large enough to enclose the desired payload and other large elements but at the same time avoiding or minimizing redundant volume. The body is configured to minimise structural mass and drag. To this end, it typically has a rounded nose segment in which the cross-section area gradually increases up to the point of maximum width and height or diameter such that the air pressure reduces in a way favourable for low drag and a tail segment, in which the cross-section area gradually decreases towards the sharp trailing edge of the body such that pressure recovery takes place without significant flow separation. There may be included between the two a segment of the body of constant cross-section area, with their surfaces joining tangentially, but this will be minimised in terms of length, preferably of zero length. Both the nose segment and tail segment are minimised in terms of relative length (relative to maximum width or height) so as to maximise the volume to surface area ratio for the required volume and to minimize bending loads in the body walls. A body of smaller fineness ratio has the advantage that the structure can be lighter and of smaller wetted surface than that of alternative arrangements of higher fineness ratio.

The trailing edge on the fuselage may be adjusted such that in steady flight at cruising speeds the fuselage contributes to the total lift of the aircraft. The lift contributed by the fuselage may compensate for the lift lost due to the interruption in the wing by the fuselage. In other words, the lift distribution over the wing and the fuselage would be the approximate equivalent to the lift distribution of a corresponding uninterrupted wing having no fuselage. This avoids the need for the wing having to be designed larger to compensate for lift lost by the presence of the fuselage which would decrease the overall efficiency of the aircraft. It would also result in the spanwise lift distribution to approximate the ideal distribution for better efficiency.

The wing may include adjustable control surfaces to provide longitudinal and lateral control and to adjust the trim or balance of the aircraft. In one embodiment of the invention, the wing may include control surfaces arranged along a trailing edge of the wing by which the spanwise lift distribution can be adjusted to approximate the ideal distribution in any flight condition.

Balance of the aircraft in flight may be achieved jointly or separately by adjusting the static margin.

The invention accordingly extends to a method of controlling an aircraft of the type described herein during flight which includes adjusting the static margin.

In one embodiment of the invention, adjustment of the static margin can be achieved by moving the relative position of the centre of gravity of the aircraft. This could be achieved by moving mass, e.g. pumping fuel or water from one location to another or by moving luggage pallets, or the like. In another embodiment of the invention this could be achieved by changing the position of the neutral point of the aircraft by, for example changing the sweep angles of at least part of the wing and/or changing the width and/or the longitudinal position of the trailing edge. To this end, an outer portion of each side of the wing may be angularly displaceable about an upwardly directed axis relative to an inner portion of each side of the wing and/or by changing the width of the fuselage flap. Further the relative position of the wing and the fuselage may be adjustable.

Changing the static margin involves changing the relative positions of the centre of gravity and the neutral point. Optimum flight efficiency can only be achieved when the centre of gravity and the centre of pressure of the ideal flow field are in register. Traditionally, for off-design positions of the centre of gravity, the centre of pressure is adjusted to agree with the location of the centre of gravity by changing the lift on the horizontal stabilizer whereby the flow field is modified and may no longer be ideal. However, by adopting procedures described above, good flight efficiency can be maintained also in off-design conditions.

The wing structure may be rooted in or close to the centre of pressure of the wing.

In a preferred embodiment of the invention, the centre of pressure of the wing and the centre of pressure of the fuselage coincide or are close to each other.

The wing may have an aspect ratio of at least 6.

According to another aspect of the invention there is provided an aircraft which includes:

a tailless fuselage; and

a wing connected to the fuselage, the wing having two sides which protrude from opposite sides of the fuselage, each side having an inner section having a first dihedral angle and an outer section having a second dihedral angle, the second dihedral angle being less than the first dihedral angle.

In a preferred embodiment of the invention, the second dihedral angle may be negative, i.e. it may be an anhedral angle.

According to another aspect of the invention there is provided an aircraft which includes:

a tailless fuselage; and

a wing connected to the fuselage, the wing having two sides which protrude from opposite sides of the fuselage, each side having an inner section, and an outer section, at least part of which is swept back.

According to another aspect of the invention, there is provided an aircraft which includes:

a tailless fuselage which has a body which has a transverse trailing edge; and

a wing connected to the fuselage, having an aspect ratio of at least 6, the wing having two sides which protrude from opposite sides of the fuselage.

A wing tip may protrude from an outer end of each side of the wing.

In one embodiment of the invention, the wing tip protrudes upwardly from the outer end of the side of the wing.

BRIEF DESCRIPTION OF DRAWINGS

The invention will now be described by way of example, with reference to the accompanying diagrammatic drawings.

In the drawings:

Figure 1 shows a three-dimensional view of an aircraft in accordance with the invention;

Figure 2 shows a top view of the aircraft of Figure 1;

Figure 3 shows a rear view of the aircraft of Figure 1;

Figure 4 shows, on an enlarged scale, a side view of the aircraft of Figure 1;

Figure 5 shows a side view of a body of the aircraft; and

Figure 6 shows a plan view of part of the aircraft.

In the drawings, reference numeral 10 refers generally to an aircraft in accordance with the invention. The aircraft 10 includes a tailless fuselage, generally indicated by reference numeral 12 and a wing 14 having two sides 14.1 connected to the fuselage 12 and extending laterally from opposite sides thereof.

The fuselage 12 includes a body, generally indicated by reference numeral 16 which terminates in a transverse trailing edge 18. In particular, the body 16 includes a hollow bulbous primary section, generally indicated by reference numeral 20 and a flap 22 which protrudes rearwardly from the primary section 20 and forms the trailing edge 18. Relative to the perpendicular X, Y and Z axes shown in Figure 1 of the drawings, when the aircraft 10 is intended for flight in the direction of the X axis, the trailing edge 18 typically extends laterally in the direction of axis Y, i.e. typically perpendicular to the flight direction X. The position of the flap 22 relative to the primary section 20 may be adjustable to permit displacement of the flap 22 about an axis which extends in the Y direction thereby permitting the trailing edge 18 to be adjusted vertically, i.e. in the Z direction. As indicated in Figure 5 of the drawings, the flap 22 is angularly displaceable about a transverse pivot axis 25 such that the trailing edge 18 is adjustable upwardly and downwardly. In Figure 5 of the drawings, the trailing edge is shown in solid lines in its neutral position and as indicated by the broken lines, it is displaceable upwardly relative to the neutral position by an angle of up to 30° and downwardly relative to the neutral position by an angle of up to 60°. Further, the flap 22 may consist of a plurality of components 19 which are laterally adjustable relative to one another in order to permit the effective width of the trailing edge 18 in the Y direction to be adjusted. With particular reference to Figure 6 of the drawings, in which, unless otherwise indicated, the same reference numerals used above are used to designate similar parts, it can be seen that the flap 22 includes a plurality of sector shaped segments 19 which are pivotally connected to a central portion 21 for pivotal displacement about vertical axes 23 which may be spaced laterally or transversely. The components 19 can be displaced between a fully extended position, as illustrated in the top half of Figure 6 of the drawings or a retracted condition in which they do not protrude laterally beyond the edges of the central position 21 as shown in the lower half of Figure 6 of the drawings. The components 19 are typically adjustable such that the width of the trailing edge 18 is adjustable to between 0.5 and 3 times the maximum width W (Figure 6) of the primary section 20 of the body 16. The effective length of the flap in the X direction is adjustable to permit the trailing edge to be longitudinally adjustable in the X direction. This can be achieved in different ways, e.g. it could be achieved by having a flap comprising two or more parts which are telescopically connected and relatively displaceable in the longitudinal direction. Another option may be for the flap to be retractable, at least part way into the primary section 20 of the body 16.

The primary section 20 of the body 16 has a fineness ratio, i.e. a ratio of length to maximum width or height of the primary section of between 3 and 7 and typically of the order of 4.5. The fineness ratio is defined as the length L divided by the effective diameter D.

As can best be seen in Figure 5 of the drawings, the length L is the length of the primary section 20 of the body 16, i.e. excluding the length of the flap 22. The Effective Diameter for a round body would be its maximum diameter, and for a non-round body, such as in the embodiment shown, it would be the square root of its maximum width W times its maximum height H (see Figures 5 and 6).

The wing 14 has on each side 14.1 an inner section 24, an outer section 26 and an outwardly and/or upwardly directed wingtip 28. The inner section 24 is forwardly swept with a positive dihedral angle. In this regard, typically, the dihedral angle is 3°. The outer section 26 is swept back with a reduced dihedral angle. In a preferred embodiment of the invention, the outer section 26 may have a negative dihedral angle, i.e. anhedral, typically 5°. The wingtip 28 extends from the outer section and in the embodiment shown is inclined upwardly. The wingtip can be inclined upwardly at an angle of inclination of up to 90° to the Y axis. In another embodiment of the invention, the wingtip forms an extension of the outer section of the wing as shown in broken lines in Figure 3 of the drawings and as indicated by reference numeral 29.

If desired, as indicated in Figure 2 of the drawings, the outer section 26 of each side 14.1 of the wing may be angularly displaceable, as indicated by arrow 30, about an upwardly directed axis, generally indicated by reference numeral 31, relative to the inner portion 24 to effect a change in the sweep angle of the wing.

Further, the wing 14 includes adjustable control surfaces, generally indicated by reference numeral 32 (Figure 2) along the trailing edge thereof to provide longitudinal and lateral control and to adjust the trim of the aircraft.

The Inventor believes that an aircraft in accordance with the invention will include numerous advantages over the prior art.

The fuselage of the current art provides for sufficient length to hold and mass balance the empennage. This either introduces fuselage volume which is not useful for any other purpose or it may lead to fuselage fineness ratios which are sub-optimal in terms of mass and drag. This invention does not employ the empennage. One advantage is then, that the central single body can therefore be shaped in favour of minimum drag and mass for the required design conditions. The resulting fineness ratio is such that the fuselage is typically shorter and may be of increased lateral dimensions when compared with the prior art. This results in lower bending moments in the structure and less surface skin, requiring less material and hence reduced mass and drag when compared to the fuselage of the current art. A further advantage is, that this shorter fuselage can be fitted with a fuselage flap rather close to the aircraft wing and centre of gravity. This can then be adjusted such that it can provide circulation or lift over the fuselage of sufficient magnitude to compensate for that which is lost by the wing due to the fuselage occupying the wing. One advantage is then, that it is in principle possible to fly the aircraft with an ideal spanwise lift distribution. Another advantage is, that the wing can be smaller and with smaller bending moments than otherwise, without the lift contribution by the fuselage.

Circulation intensity over the fuselage can be controlled by means of adjusting the size and the angle of the fuselage flap. This can then be used in conjunction with the high-lift devices on the wing to offer a very high combined lift coefficient for the flight body. One advantage then is, that the effective wing loading can be reduced by fully spreading the flap to its widest size and/or extending the flap during flight phases where this is desirable like during takeoff, turning and loitering. Another advantage is that the flap system can be set to reduce effective wing loading as mentioned above and additionally increasing its lift coefficient and drag coefficient during flight phases where this is desirable like during approach and landing. Thus, the current invention provides for a fuselage which can make a significant contribution to the total lift when required. This has advantageous implications on the design size and mass of the wing and the requirement for the high lift devices on the wing.

The trailing edge of the fuselage of this invention bestows an aerodynamic centre on the fuselage. The advantage of this is that the fuselage can then be longitudinally statically stable and therefore it does not require the additional horizontal stabilizer wing of the current art.

Another advantage of this arrangement is that the adjustment of the flap can change the position of the aerodynamic centre and the centre of pressure and it can therefore be used to control circulation, the pitching moment and the damping. It can also be used as an airbrake for descent angle control or in an emergency dive.

The central fuselage of this invention may have to be wider than that of the comparable current art. This has the advantage that, for a given span of wing, the length of the exposed wing is shorter with structural mass benefits on the wing bending structure.

A wing flying in the wake of another, like the tail wing of the current art flying in the wake of the main wing, encounters disturbed air while also distorting the flow field of the leading wing. The wake behind a multi-wing aircraft is a complex flow field in which all induced disturbances are combined. It is difficult to avoid a penalty on flight economy when using such an arrangement of wings as used in the typical current art. In contrast, the current invention provides for an aircraft in which the flow over its wing and fuselage is not adversely disturbed by another wing, neither leading nor trailing.

Yet another advantage of the invention is that it provides for a flight body to which the wing can offer an appropriate pitch curve slope to provide, in combination with the stable fuselage the desired overall longitudinal static stability. Further, the wing offers suitable lateral stability to have, in combination with the fuselage the desired lateral stability properties.

The vertical stabilizing and controlling wing found in the typical current art has mass and causes drag while it is making no positive contribution to the flight economy. The present invention provides for a flight body layout which can do without it. To help achieve desirable properties for lateral stability, control, damping and trim, this invention provides the outer wing portions and the wingtips. Depending on the required combination of properties these tips can be arranged either as mere extensions of the outer wing portion or they can be angled upwardly relative to the outer wing portion. Their twist relative to the outer wing portion can be used to tailor the lift distribution suitable in terms of pro-verse yaw (avoiding adverse yaw) and wing tip stalling (avoiding wing tip stalling) but, their effective twist can also be such that they make a positive contribution to the flight economy during normal flight.

The control strategy for pitch trim of the current art usually imposes a penalty on flight economy. In contrast, this invention provides for a control strategy for pitch trim which can in principle be without this penalty.

The downwash profile in the wake of a flight body of the current art is usually not ideal, in other words, span efficiency is usually compromised. This invention allows for the manipulation of the wing and fuselage geometry to maintain the ideal lift distribution to induce the ideal downwash profile at all useful flight conditions, in other words, the span efficiency does not have to be compromised.

The fuselage typical of the current art protrudes rearwardly from the landing gear to an extent which limits the angle of aircraft nose-up attitude when on or near the ground. In contrast, the invention provides for a flight body in which the reduced rearward extent of the fuselage allows a higher nose-up attitude. Then the fuselage and wing can operate at higher angles of attack to exploit their respective maximum circulation. In such condition of operation the drag is also high which may be useful, for example, to allow for a steeper approach path during landing and/or a shorter roll-out after touch-down.

Tilt rotor or tilt wing aircraft or other VTOL aircraft of the current art require complex structures and mechanism to tilt either the engine nacelle or jet ducts or the entire wing on the fuselage for vertical takeoff and or landing and to change their tilt angle during flight for normal flight. Fan or jet driven VTOL aircraft of the current art may alternatively include elaborate secondary ducts. The shorter fuselage of the current invention offers the opportunity to provide a flight body which can be tilted to a nose-up attitude such that its main propelling rotors, fans or jets could act as lifting devices for vertical takeoff and or landing without any changes to the flight body and which can remain unchanged as thrusting devices for normal flight.

The arrangement of the wing of the current invention allows for the wing tip clearance to be made as desired for exploitation of the ground effect. This can be useful on any aircraft during takeoff and landing but in particular it may be useful in wing-in-ground effect vehicles. The configuration of the current invention is therefore suitable to such wing-in-ground effect vehicles but it is also suitable to offer good short-field operation properties for normal aircraft.

In the typical current art wing tip clearance when on the ground is not, in general an independent design variable. It depends from the vertical position of the wing, its span, sweep and dihedral angle and the length of the undercarriage. To provide acceptable wing tip clearance, the lateral stability properties of the flight body are sometimes compromised. The main wing arrangement of the current invention allows for the additional wing design variables of inner wing sweep and dihedral such that wing tip clearance is an independent design variable by which such compromise, like the tendency to Dutch roll, can be avoided.

This invention provides for a flight body in which the primary wing structure can be rooted in or close to the centre of pressure of the wing. It is desirable to have the centre of pressure of the wing and that of the fuselage in close proximity to each other, ideally to coincide. For balanced flight the flight body centre of gravity needs to coincide with the flight body centre of pressure. Therefore, this invention provides for a layout in which the primary wing structure can root in or close to the centre of gravity. This is advantageous in terms of structural load paths and aero-elastic properties to allow for a flight body that is lighter than that of much of the current art.

CLAIMS

1. An aircraft which includes:

   a tailless fuselage which has a body which includes a transverse trailing edge, the body having a fineness ratio of between 3 and 7; and

   a wing having two sides which protrude from opposite sides of the fuselage.

2. An aircraft as claimed in claim 1, in which the fineness ratio is 4.5.

3. An aircraft as claimed in claim 1 or claim 2, which includes a power source for propelling the aircraft.

4. An aircraft as claimed in any one of the preceding claims, in which the trailing edge of the fuselage is adjustable.

5. An aircraft as claimed in claim 4, in which the body includes a bulbous primary section and a flap which forms the trailing edge, the flap being connected to and displaceable relative to the primary section to permit adjustment of the trailing edge.

6. An aircraft as claimed in claim 5, in which the flap is displaceable relative to the primary section about a transverse axis.

7. An aircraft as claimed in claim 6, in which the flap is displaceable upwardly relative to a neutral position by up to 30° and downwardly relative to the neutral position by up to 60°.

8. An aircraft as claimed in any one of claims 5 to 7, in which the width of the trailing edge is adjustable.

9. An aircraft as claimed in claim 8, in which the flap includes a plurality of transversely spaced sections which are laterally displaceable relative to one another in order to increase or decrease the width of the trailing edge.

10. An aircraft as claimed in claim 8 or claim 9, in which the width of the trailing edge is adjustable between 0.5 and 3 times the maximum width of the primary section of the body.

11. An aircraft as claimed in any one of claims 5 to 10, in which the position of the trailing edge is longitudinally adjustable.

12. An aircraft as claimed in claim 11, in which the effective length of the flap is adjustable to permit adjustment of the longitudinal position of the trailing edge.

13. An aircraft as claimed in any one of the preceding claims, in which each side of the wing has an inner section which is inclined upwardly away from the body and an outer section which is inclined downwardly.

14. An aircraft as claimed in any one of the preceding claims, in which at least a portion of each side of the wing is swept back.

15. An aircraft as claimed in any one of the preceding claims, in which an inner section of each side of the wing is swept forward with a positive dihedral and an outer section of each side of the wing is swept back with a negative dihedral.

16. An aircraft as claimed in claim 15, in which a sweep angle defined on a quarter chord line of the inner section of each side of the wing is approximately 5° forward and a sweep angle defined on a quarter chord line of the outer section of each side of the wing is approximately 25° backward.

17. An aircraft as claimed in any one of the preceding claims, in which the wing is arranged in a shoulder wing position and the inner wing dihedral of each side of the wing is approximately 3° and the outer wing anhedral of each side of the wing is approximately 5°.

18. An aircraft as claimed in any one of the preceding claims, in which the fuselage is configured such that in steady flight at cruising speeds it contributes to the total lift of the aircraft.

19. An aircraft as claimed in claim 18, in which the lift contributed by the fuselage compensates for the lift lost due to the interruption in the wing by the fuselage.

20. An aircraft as claimed in any one of the preceding claims, in which the wing includes adjustable control surfaces to provide longitudinal and lateral control and to adjust the trim of the aircraft.

21. An aircraft as claimed in claim 20 in which the wing includes control surfaces arranged along a trailing edge of the wing by which the spanwise lift distribution can be adjusted to approximately an ideal distribution in any flight condition.

22. An aircraft as claimed in any one of the preceding claims, in which static margin is adjustable in flight.

23. An aircraft as claimed in claim 22, in which static margin is adjustable by moving the relative position of the centre of gravity of the aircraft.

24. An aircraft as claimed in claim 23, in which the centre of gravity of the aircraft is moved by displacing mass within the aircraft.

25. An aircraft as claimed in claim 24, in which the mass which is moved is at least one of fuel, water, one or more engine(s), battery(ies), ballast, undercarriage, and/or payload.

26. An aircraft as claimed in any one of claims 22 to 25, in which the static margin is adjusted by changing the position of the neutral point of the aircraft.

27. An aircraft as claimed in claim 26, in which the position of the neutral point is adjusted by changing the sweep angle of at least part of the wing.

28. An aircraft as claimed in claim 27, in which an outer portion of each side of the wing is angularly displaceable about an upwardly directed axis relative to an inner portion of each side of the wing to effect a change in the sweep angle of the wing.

29. An aircraft as claimed in any one of claims 26 to 28, in which the position of the neutral point is changed by changing the width and/or the longitudinal position of the trailing edge.

30. An aircraft as claimed in any one of claims 26 to 29, in which the position of the neutral point is changed by adjusting the relative position of the wing and the fuselage.

31. An aircraft as claimed in any one of the preceding claims, in which the wing has an aspect ratio of at least 6.

32. An aircraft which includes:

a tailless fuselage; and

a wing connected to the fuselage, the wing having two sides which protrude from opposite sides of the fuselage, each side having an inner section having a first dihedral angle and an outer section having a second dihedral angle, the second dihedral angle being less than the first dihedral angle.

33. An aircraft as claimed in claim32, in which the second dihedral angle is negative.

34. An aircraft which includes:

a tailless fuselage; and

a wing connected to the fuselage, the wing having two sides which protrude from opposite sides of the fuselage, each side having an inner section, and an outer section, at least part of which is swept back.

35. An aircraft which includes:

a tailless fuselage which has a body which has a transverse trailing edge; and

a wing connected to the fuselage, having an aspect ratio of at least 6, the wing having two sides which protrude from opposite sides of the fuselage.

36. An aircraft as claimed any one of the preceding claims, in which a wingtip protrudes from an outer end of each outer section of the wing.

37. An aircraft as claimed in claim 36, in which the wing tip protrudes upwardly from the outer section of the wing.

38. A method of controlling an aircraft as claimed in any one of the preceding claims, in flight, which method includes adjusting the static margin.

39. A method as claimed in claim 38, in which static margin is adjustable by moving the relative position of the centre of gravity of the aircraft.

40. A method as claimed in claim 39, in which the centre of gravity of the aircraft is moved by displacing mass within the aircraft.

41. A method as claimed in claim 40, in which the mass which is moved is at least one of fuel, water, one or more engines, ballast, undercarriage and/or payload.

42. A method as claimed in any one of claims 38 to 41, in which the static margin is adjusted by changing the position of the neutral point of the aircraft.

43. A method as claimed in claim 42, in which the position of the neutral point is adjusted by changing the sweep angle of at least part of the wing.

44. A method as claimed in claim 42 or claim 43, in which the position of the neutral point is adjusted by changing the width and/or the longitudinal positon of the trailing edge.

ABSTRACT

The invention relates to an aircraft having a tailless fuselage. The fuselage has a body which includes a transverse trailing edge. The aircraft further includes a wing having two sides which protrude from opposite sides of the fuselage. The body typically has a fineness ratio of between 3 and 7. Each side of the wing has an inner section having a first dihedral angle and an outer section having a second dihedral angle, the second dihedral angle being less than the first dihedral angle. At least part of the outer section is typically swept back. The configuration of the aircraft provides it with improved flight efficiency.

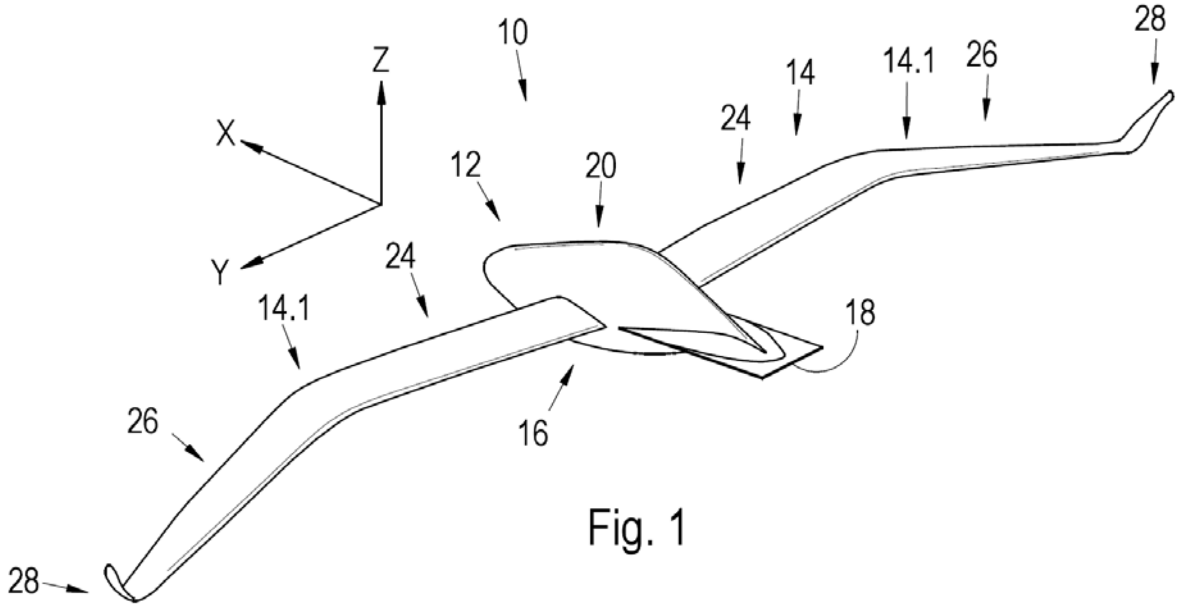


Fig. 1

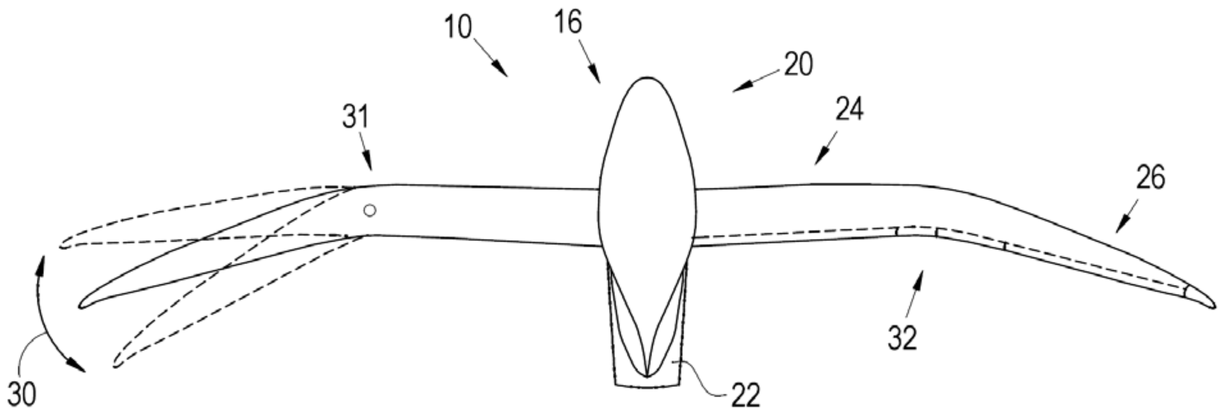


Fig. 2

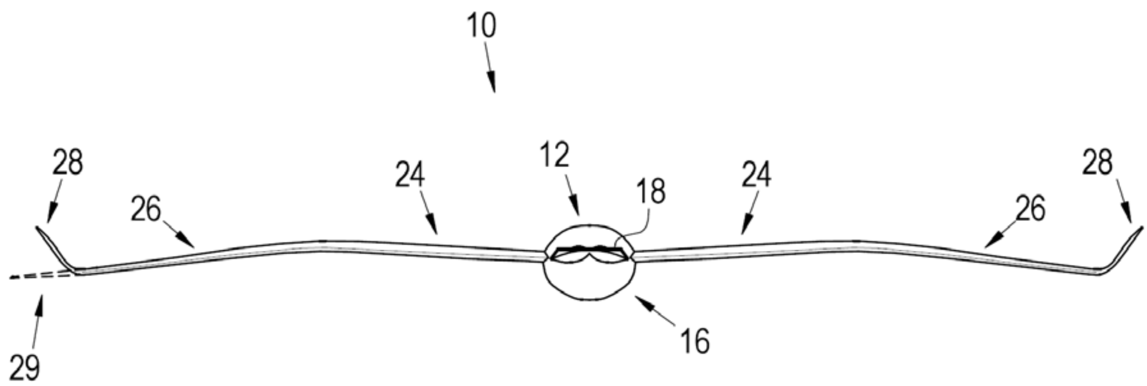


Fig. 3

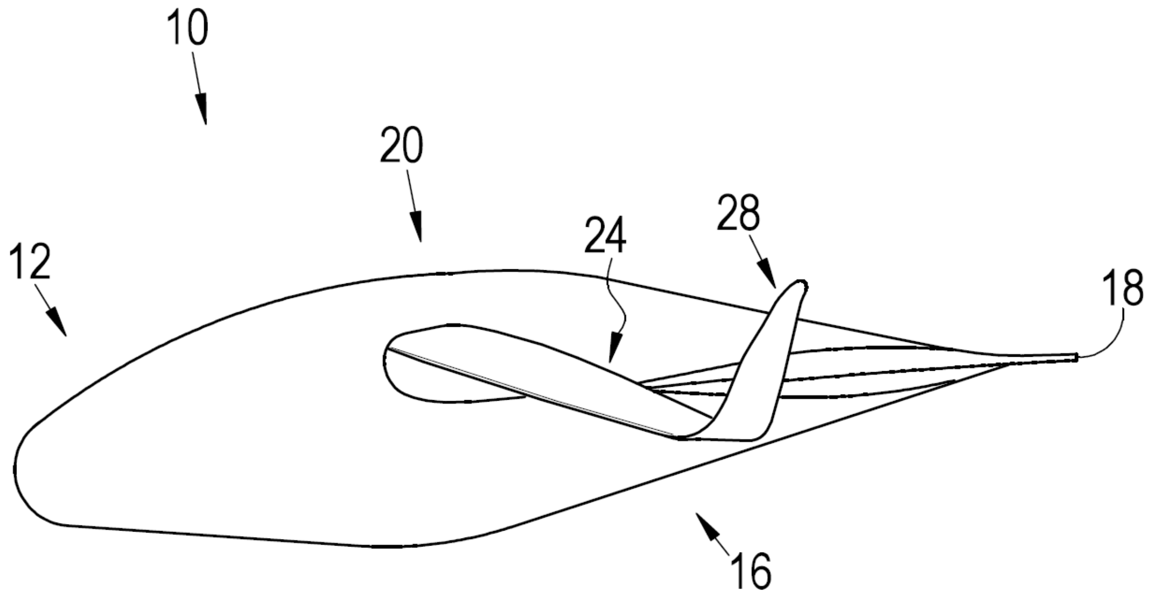


Fig. 4

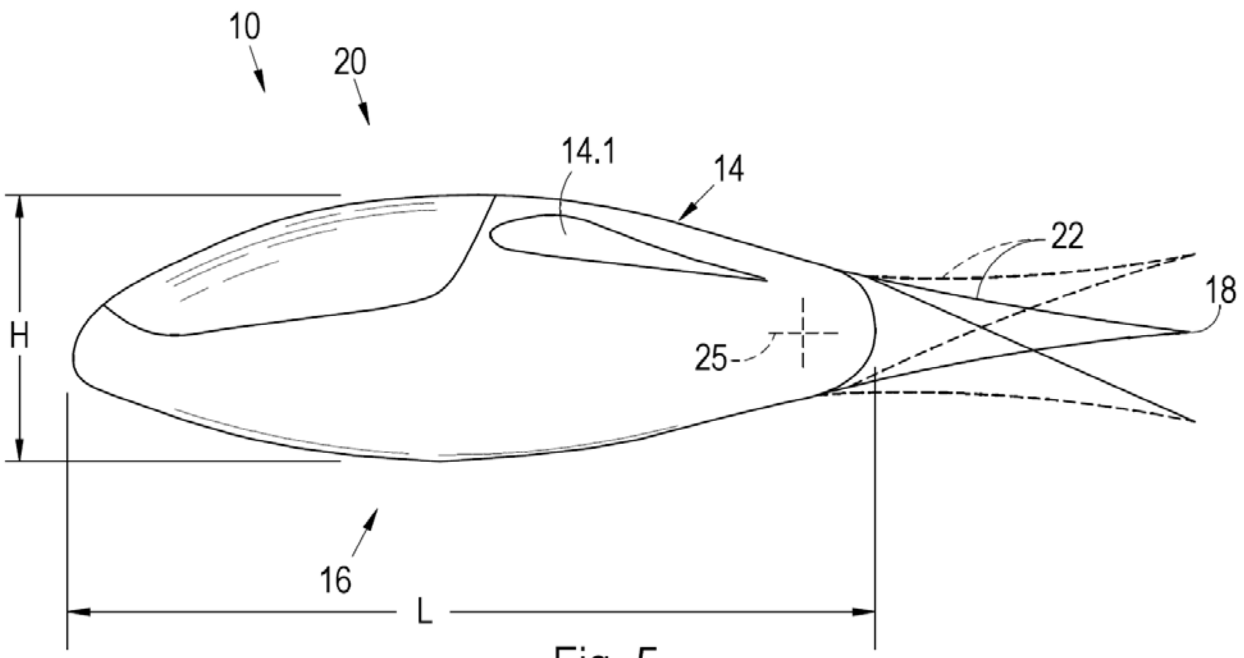


Fig. 5

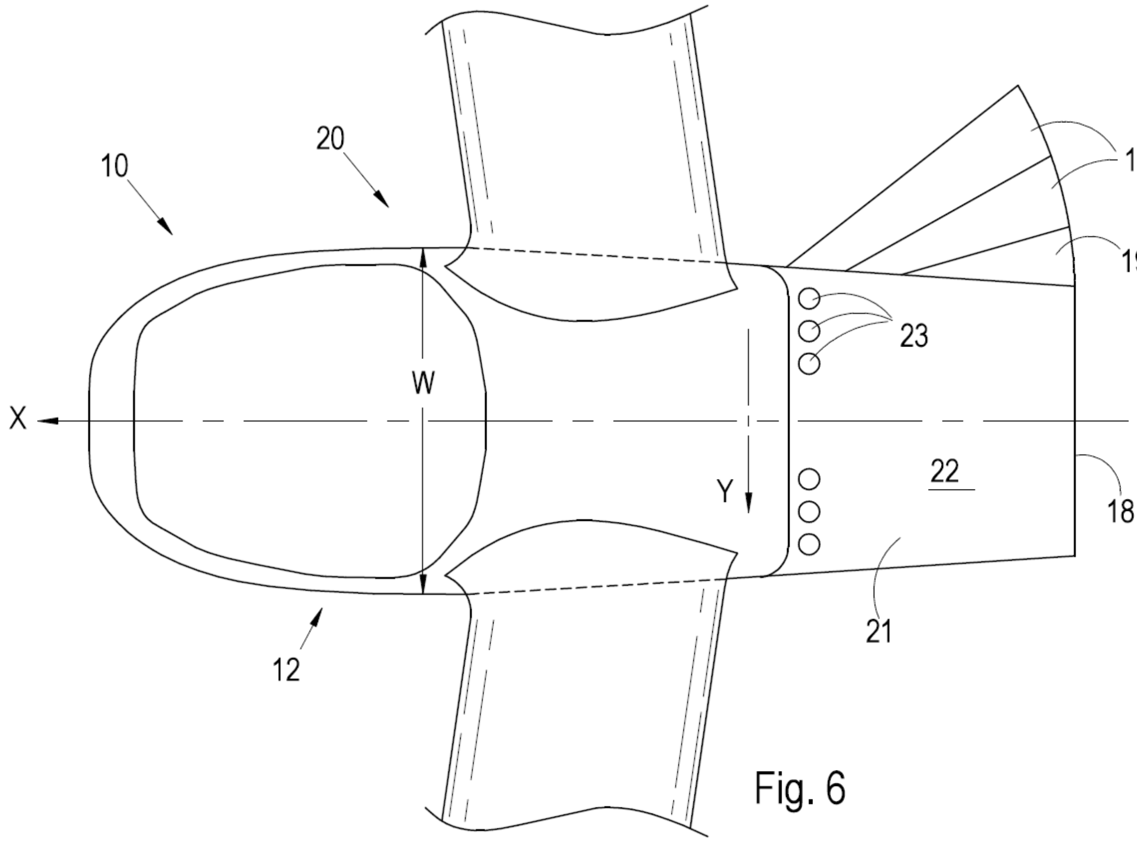


Fig. 6

Appendix E

Radio-Controlled Models

Figure E1 shows the motorised Exulans model with the flap set for landing. The ¼ scale radio-controlled models shared a wing of 3 m span used on either a glider fuselage or on an electrically powered fuselage with tricycle gears, as seen here.

E.1 Purpose of the Models

Give that the academic environment in which this development took place was not suitable for real manned flight testing, radio-controlled models had to be employed for the actual real free flights. This appendix offers some additional illustrations of the two ¼ models which were developed for this purpose. The purposes of these models were specifically:

- to allow flight in the free-state wind tunnel for close observation of control responses;
- to allow actual free flight to assess the handling qualities;
- to perform flight mechanical observations;
- to try runway operations with a tricycle undercarriage;
- to try winch launching;
- to try flight in turbulent conditions;
- to test the use of controllable winglets;
- to test control by variable wing sweep in actual flight;
- to investigate the response to flap deployment;
- to investigate adverse yaw in actual flight;
- to test the design concept of concentrated tubular wing structures;
- to get some general experience with design and operation of the gull-wing configuration;
- to try packaging arrangements for trailer transportation;
- to serve as a demonstrator.

E.2 Wing Structure

Figure E2 shows the primary skeletal wing and fuselage structure of the glider model and it shows how the tubular main spar was integrated into the wing. Here it can be seen how the primary tubular structure of the outer wing is integrated with balsa ribs to give the aerodynamic shape.

The ¼ scale models shared the same wing with a glider fuselage and an electrically motorised fuselage. The primary wing structure was made by filament winding to produce tubular main spars with integrated wing joints. In this way the mass penalty of joints could be minimised as load paths could easily be concentrated into the joint inserts. By this approach, the rib and wing skin structure are non-critical as they are not part of the primary structure.

E.3 Radio-Controlled Glider

Figure E3 Here the glider is about to be hand-launched into a 10 m/s see-breeze on a 100 m dune in the Cape in South Africa. These offered very turbulent flying conditions when close to terrain but the pilot had very responsive control to deal with such disturbances. Test manoeuvres would be flown away from the dune and when done the glider would be returned into the ridge-lift to recover lost height. Battery life or daylight rather than the wind would dictate the length of a flight once good wind conditions prevailed.

The glider of 3 m span was typically flown at 4 kg all-up mass. Most of the flight testing was done using the ridge-lift off a coastal dune where steady sea-breezes would allow for long gliding flights in turbulent conditions. The model glider was also tried on the winch to test if any problems with such launch technique should be expected.

On some flights, a video camera inside the fuselage would be pointed towards a wingtip to observe the wingtip excursions for the yaw-roll coupling investigations. Attempts at instrumenting the glider with accelerometers, rate gyros, magnetometer and data loggers were given up when interference by the instrumentation with the radio-control signal kept causing hazards. Video recordings from the ground and from the aircraft seemed sufficient to answer the questions in this preliminary investigation.

Figure E4 The model glider is hooked to a F3B winch by a Y link to a pair of CG hooks. After a short run on the ground cover the model would pitch up into an almost vertical climb.

E.4 Motorised Model

Figure E5 The electrically motorised model during take-off and landing on a tarred model runway.

For the investigations of the practicalities concerning runway operations, it was necessary to have a motorised version of the gull-wing model. With the undercarriage being under investigation replaceable modules were made for testing of different stiffness combinations. The main gear strut was made from carbon fibre which then served as an un-damped spring suspension. The steerable front wheel had a coil spring in a linear suspension with friction damping. The front strut was arranged to offer propeller protection against ground-strike.

Figure E6 Note the fuselage aft body ready to be fitted with a fuselage trailing edge.

While the focus of these model investigations was on the proto-flyer it can be seen that the fuselage has an aft-body shape ready for the investigations of the fuselage trailing edge. For such tests a controlled fuselage flap is to be implemented.

Appendix F

Exulans I, the Full-Scale Prototype

Figure F1 Exulans I resting on its landing skid on a glider runway while testing controls in a strong steady wind.

This section offers some additional information and illustrations about the Exulans I which may be of interest in the context of the main discussion. A full discussion on the design of the prototype is given in the Master Thesis of the author.

F.1 Purpose of the Full-Scale Prototype

Exulans I was designed and build as a test vehicle for flight mechanic investigations with the pilot in the control loop. It was designed as an ultra-light low wing-loading glider which could be operated at relatively low speed within the safe bounds of vehicle mounted test rigs. The purposes of this prototype were specifically:

- to perform actual controlled full-scale flight on a vehicle mounted test rig;
- to test pitch, roll and yaw control by means of the elevons;
- to test the pitch response to flap deflection;
- to test the wingtip airbrakes for yaw control;
- to test the wing sweep system for trim control and active pitch control;
- to perform flight mechanical investigations;
- to evaluate static and dynamic stability properties of the gull-wing layout;
- to investigate adverse yaw and pilot induced oscillations;
- to assess the ergonomics of the unassisted control of the wing sweep system;
- to evaluate the handling qualities of the gull-wing layout;
- to compare trimming by elevon vs trimming by variable sweep.

F.2 Main Parameters

Wing Area	12	m^2
Wing Span	12	m
Aspec Ratio	12	
Empty Mass	60	kg
All-up Mass	150	kg
Stall Speed	40	km/h

Figure F2 Exulans I as it would be carried by the pilot in the foot launch position.

F.3 Materials and Construction

The primary wing structure and many of the structural components were made from carbon fibre. Also the wing skin of the D-box of the inner wing used woven carbon fibre in 3.6 mm Nomex honeycomb sandwich. The remainder of the wing used a light Kevlar skin in a similar sandwich. Aircraft grade post-cured epoxy resin was used throughout. Wing skins were made in negative wing moulds by hand layup using a special resin dispenser to ensure consistent resin distributions. Spars and ribs were bonded into the skins in the moulds before the wings halves were closed by bonding. All wing elements were first aligned in an assembly jig before committing the wing joint inserts into their final positions.

Figure F3 shows a hand lay-up in progress of the inner wing upper surface in a negative mould using a special resin dispenser. The carbon fibre in the D-box portion and the Kevlar in the rear wing skin can be seen after the outer layer of the sandwich was cured in a vacuum bag.

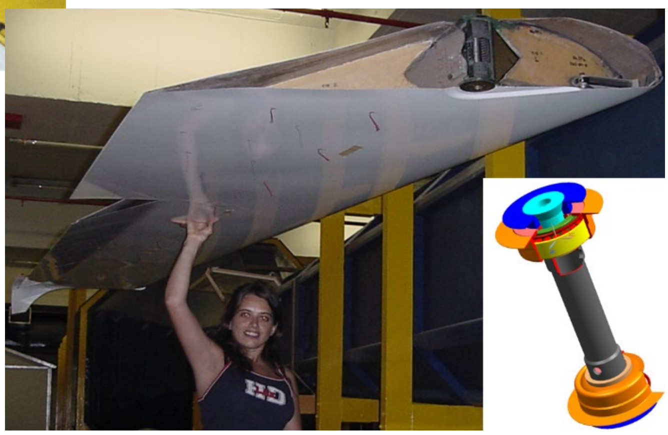
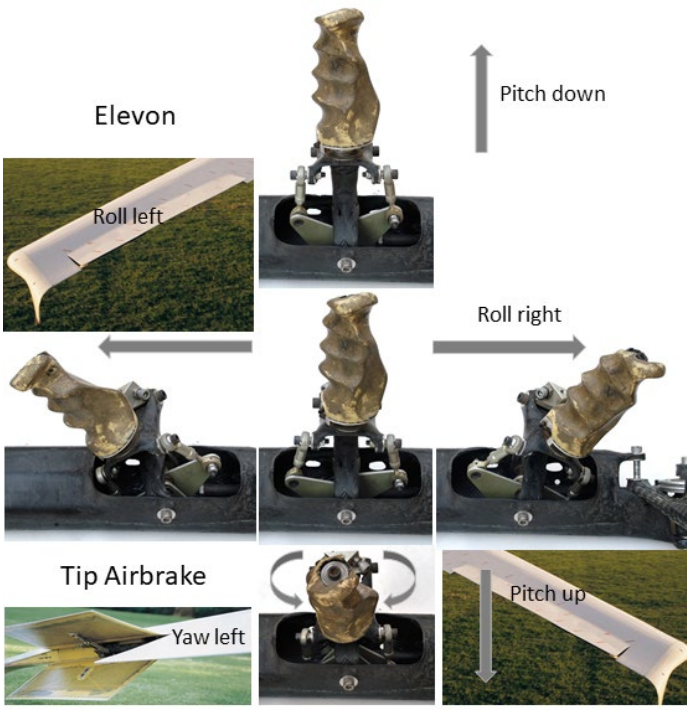


Figure F4 shows the outer wing of only 7 kg which included the wing sweep hinge (insert) of 0.8 kg.

F.4 Structural Testing

The wing structure was tested in a whiffle tree to a load factor of +5.5 G and -3.5 G. Controls were also tested with the wing under load. Also the wing sweep system was actuated under load however not at the full loading as this would cause unnatural internal reaction loads unlike the control response which would result in flight.

F.5 Controls



The pilot in the prone position would control the elevons by a control stick in his right hand, mounted on the horizontal control bar at the end of the pair of sweep levers. Mechanical mixing for pitch and roll would happen in the stick mechanism, from where pushrods and then cables transferred the motion to the single control surface in each wing. A carbon fibre torque tube within the elevon would deform the wing trailing edge on a gapless skin hinge. Diagonal movement of the stick would activate only one surface. The same control stick could be twisted to open either the left or the right wingtip airbrake on the end of the elevon for yaw control. This would split apart the outer 0.6 m of the 2 m elevon to cause a drag imbalance.

The flap on the inner wing would be set into locked positions by the left hand. The upper position would give the aerofoil some reflex with the flap at -6°. The lowest position of high drag at 45° would be used for landing. The flap running on a pair of shaped guide-rails would initially extend to increase the chord by about 10 % before beginning to deflect down. Also the flap had a gapless flexible skin hinge but only in the lower surface.

F.6 Wing Sweep System

For testing of a mode of static margin control the glider needed a system of active wing articulation. In bird flight one may readily observe that the bird uses movement of the hand wing for purposes of control. Although their articulations can be controlled on all axes, the forward-backward sweep motion seems most important to the bird and it is assumed to be used for pitch control. To test its usefulness for pitch control the Exulans I therefore was fitted with an active articulation in the wing wrist to allow sweeping of the outer wing between 21° and 6°. This system had to be operated by the unassisted pilot to find out if the ergonomics of control for such a system would be acceptable.

F.6.1 System Requirements

- The outer wing must only move when activated by the pilot. Flight loads of inertia, gravity and aerodynamics should not change the wing sweep angle in any attitude or manoeuvre of flight. This would be referred to as the *self-locking feature* which implies that the wing is locked into a rigid posture when the pilot is not activating the sweep system.
- The system should offer some form of overload protection against extraordinary loads such as wing contact with an obstacle. This may include inertial loads for example from tumbling. Thus, if the wing touches the ground it could yield in the sweep actuator to sweep back to relieve the reaction load. Or, if tumbling the wing could become swept back to increase pitch damping. This would be referred to as the *slip load*.
- The system must be tolerant to the environmental variables of moisture, temperature and pressure. Thus, the sweep hinge for example must be water tight (or tolerant) even if exposed to a pressure difference.
- The system should be activated by the arms of the pilot thus using his/her upper body muscle group to do the control work. This must be achievable by the 95th percentile pilot in terms of strength throughout a day-long flight.

F.6.2 System Description

Hydraulic actuation was selected for the self-locking wing sweep system. This included a pair of double acting hydraulic cylinders in the cockpit and another identical pair at the wing joint. The input cylinder would receive a large force for a small displacement taking advantage of the leverage of the sweep lever on which the pilot acts. The same force and displacement would then be available at the wing joint actuators. The pair of sweep levers had their hinges close to pilot shoulder joints. They were joined at the bottom by control bar.

Close to the output cylinder, a double channel pilot valve was installed into the transmission lines. This would open the lines when input pressure was given and otherwise it would block both lines so that the output

Figure F7 shows one of the pair of sweep levers with the input hydraulic cylinder which would be mounted in the cockpit. The pilot valves modules and a cut-away section of the carbon fibre hydraulic cylinder are also shown. The cutaway of the wing sweep hinge shows the roller bearing in the outer wing and shows the parts which join the inner wing.

cylinder would be locked. The custom made valve module had the facility for filling and bleeding the system to ensure play-free actuation. It also had internal bypass ports with an adjustable overpressure gate which would facilitate damped motion of the wing if loads exceeded the normal flight loads. If such slipping would occur one would have to apply an opposite slip load to the wing to slip it back into the position which matches that of the input lever.

At each sweep hinge the carbon fibre spar caps of the inner and the outer wing would pass their loads through steel inserts to a pair of tapered roller bearings in an O-ring sealed compartment. The hinge assembly was part of the outer wing main spar and would be joined to the inner wing by a pair of shear plugs which required the single assembly tool, a M5 Allen key to be secured into place. With the same key a quick-joint to the actuator cylinder could be secured.

In the system as embodied in Exulans I the full-range sweep change from 21° to 36° could be done in about 1 second without big effort. This would require a control bar displacement of about 0.5 m. The main resistance to fast motion would come from the hydraulic flow resistance in the rather small transmission pipes.

Appendix G

Free-State Wind Tunnel

Figure G1 The ¼ scale model glider of the Exulans is here flying at about 60 km/h under radio-control. The 3 m mass-balanced boom allows vertical and side-ways excursions (2 m and 2 m to either side) while providing thrust via a ball-joint in the centre of gravity of the aircraft. The pilot can arrest the boom from exaggerated excursions if necessary

G.1 Purpose of Facility

Given the uncertainties and risks of flying an aircraft of an unknown configuration, the radio-controlled model glider was first to be qualified for actual flight within the safe bounds of a test rig which allowed sufficient freedom of motion so that the forces of flight would express the real flight response. The purposes of this facility were specifically:

- to allow actual controlled flight but without the risk of take-off and landing;
- to provide thrust but without requiring a flight-ready propulsion system;
- to offer safety restraints in case of unexpected flight behaviour;
- to allow close observation of the aircraft in flight;
- to find the best position for the aircraft centre of gravity;

- to test the control response of the elevons, the winglets, the flaps and wing sweep system;
- to set the control gains and the servo mixing of the radio-control system;
- to allow flight with side-slip to test the slip -roll coupling (dihedral effect);
- to for test adverse yaw from roll inputs and from rolling flight;
- to allow airspeed variations to test different trimming strategies;
- to allow pilot controlled flight for assessment of the aircraft handling qualities.

The facility also served for pilot training and to qualify the aircraft for actual flight.

G.2 Description

This facility is mounted onto a small pick-up truck or on a roof carrier of a normal sedan (as shown here). The aircraft is held by a ball joint in its centre of gravity which allows all three rotational degrees of freedom. The ball joint on top of a vertical sting sits at the front of a 3 m long boom which pivots sideways and vertically on a vertical mast. The boom and sting are mass-balanced around the mast pivot to not add weight to the aircraft. The aircraft receives thrust through the ball joint while free to translate vertically and sideways and to rotate around all three axes. The pilot takes care of the boom supervision by having the boom handle attached to his harness to arrest boom excursions if necessary. In normal flight the boom is manipulated by the aircraft while the pilot maintains slack in the sling to his harness.

G.3 Method of Use

The pilot would let the boom rest in the low central position and communicate to the driver via intercom when ready for flight. The glider might be in any arbitrary attitude, perhaps against the limiters in the system. Its stability properties would soon bring it into the flight attitude as the vehicle increases speed and the controls would soon become responsive. Beyond the stall speed the glider could be lifted off and flown anywhere within the useable envelope of about 2 m vertical and 4 m horizontal extent. While the vehicle can be driven in any way and in windy or turbulent conditions with the glider following it, most tests would be done in calm conditions on a straight track.

All control variables could be tested and aggressive control inputs could be applied. These tests were used to fly the model with and without the winglets to observe the difference in yaw stability, damping and in terms of adverse yaw. Suitable parameters for the control gains and control mixing were found and an appropriate position for the centre of gravity was selected for later flight tests. By side-slipping the dihedral effect could be observed. By applying strong roll inputs and allowing fast roll rates adverse yaw could be studied at close range over a range of control inputs.

G.4 Closing Remark

It did not require too much practice before the model could be flown vigorously within the envelope of this test facility by the pilot alone, an activity which became a bit of a game for the fun of it. The name for this contraption emerged in a design review meeting when it was noted that one needs a farmers truck and lots of open space to give the aircraft a free state of motion in the wind. The vast and flat Free-State Province in South Africa can offer all of this. Since then this useful concept is known as the Free-State Wind Tunnel and has been used for tests of other experimental aircraft.

Appendix H

Pitch Test Facility

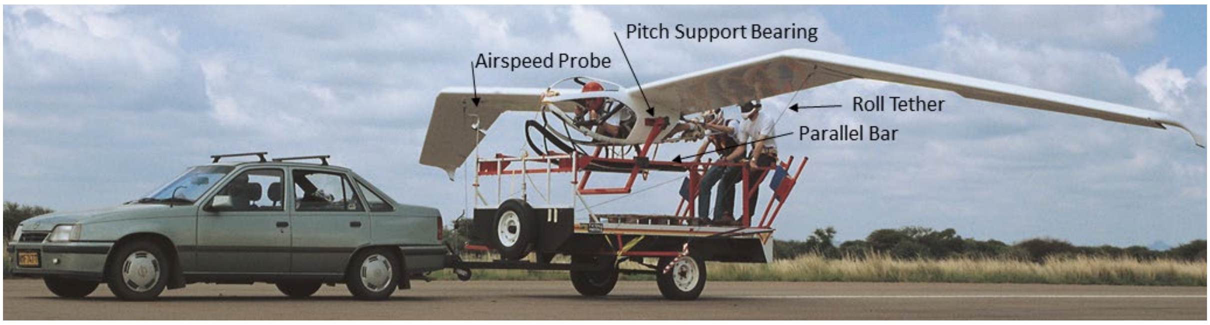


Figure H1 Exulans I in the pitch test facility with the pilot holding the controls in the stick-fixed condition and one operator holding the attitude to measure the pitch response at different angles of attack.

H.1 Purpose of Facility

Before any actual flight tests could be done, the full-scale Exulans I needed to be tested in terms of its static longitudinal flight mechanic properties within and beyond the edges of the flight envelope. This needed to be done under close observation in a controlled, systematic manner, safe for the pilot in the aircraft and the equipment. The purposes were specifically to find:

- the pitching moment vs angle of attack around several reference points so that the position of the neutral point could be derived;
- the pitching moment vs elevon deflection angle to test elevon effectiveness and control forces;
- the pitching moment vs flap deflection to test the influence of inner wing camber on the trim of the aircraft;
- the pitching moment vs outer wing sweep angle to test the control response to sweep changes;
- the flow separation patterns and sequences to find the pitch response to flow separation;
- the pitching moment beyond the edges of the normal flight envelope to see if any risky behaviour could be expected.

The facility also served to check that all control systems had the required kinematics under aerodynamic load and that the systems where structurally and ergonomically sound. It allowed to establish the work load on the pilot to activate the wing sweep system at any aircraft angle and under reasonable air loads.

H.2 Description

A flat-bed trailer was fitted with a flexible pair of longitudinal parallel bars which supported the glider on pitch bearings on a pitch axis. The attachment location on both sides of the fuselage could be adjusted. The flexibility in the bars allowed a measure of vertical excursions and gave a little rotational freedom about the roll axis. Roll excursions were limited by tethers from a cross bar to the sweep hinges of the glider. This 'softness' served to isolate vehicle terrain response from the aircraft and to give the pilot and operator a sense of the lift force and the rolling moment. The mounting height of the glider was such that the pilot could stand on the platform as if on a takeoff for a foot launch. The aircraft centre of gravity could be adjusted to coincide with the pitch axis. The trailer also served to transport the disassembled glider to the test field.

Figure H2 Exulans I disassembled and packed for transportation.

H.3 Method of Use

Additional to the driver of the car and the pilot in the glider one or two operators were suspended on the back of the rig. One operator held the tail boom to set the aircraft attitude (and thus angle of attack) and to feel the direction and relative magnitude of the pitching moment around the pitch axis while the other took pictures and records as needed. All team members were in wired open communication through microphones and headphones in their helmets. Test were done in early morning windless conditions on a tarred runway (2000m x 30m) of an out-of-use airfield at 1400m above sea-level.

With the car traveling at the desired test airspeed between 15 and 20m/s and with elevons, flaps and outer wing sweep angles as variables, the pitch curves were established for different locations of the pitch axis. The pilot held the required control settings (stick fixed in pitch, while actively keeping the wings level with roll control) while the operator did an alpha sweep from negative angles of attack up to positive angles, on both ends exploring beyond the flow separations angles. The direction and relative strength of the pitching moments were recorded against pitch angle and the trim angle was found for each set of variables. In this way the pitch curves with their trim intersections were established. In addition, the separation patters were observed as these emerged beyond the limiting angles of attack. Both operators had a clear view on tufts on the wing, both on top and below to observe the onset of flow reversal and the development of separation.

Appendix I

Vehicle Mounted Tethered Flight Test Facility

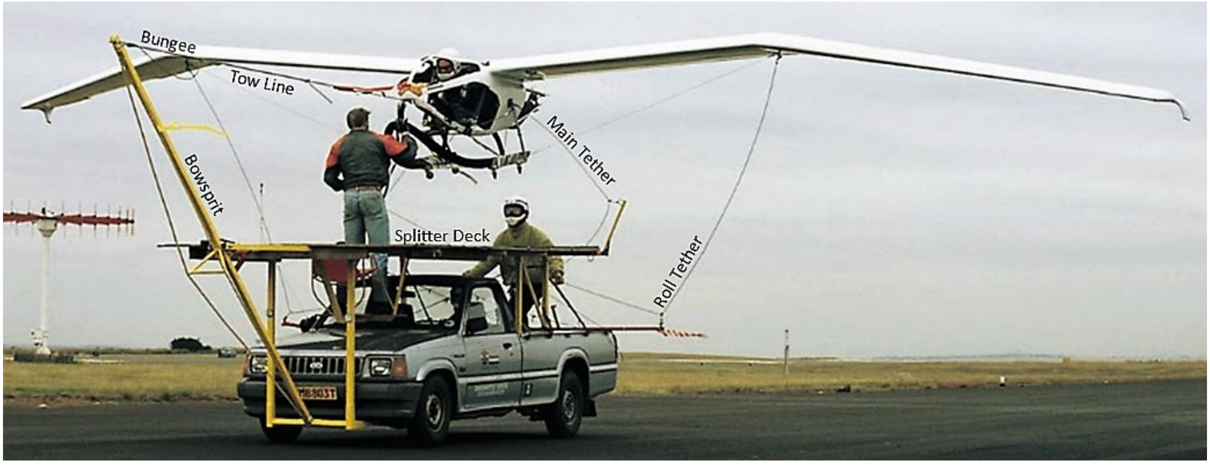


Figure I1 With the airspeed about 60 km/h the Exulans I is here flying about 4 m above the taxiway of the Swartkops air force Base, Pretoria, while the front operator is about to disturb the flight with a strong pitch input to simulate a gust.

Figure I2 Exulans I flying over the splitter deck with flaps down in the landing setting. The front operator is sitting with a slack nose rope in his hand. Also the tether operator, hardly visible in the back minimises his flow obstruction by retreating below the deck while he ensures that the tethers are slack.

Purpose of Facility

Exulans I was designed and build as a test vehicle for flight mechanic investigations with the pilot in the loop. It was designed as an ultra-light low wing loading aircraft which could be operated at low dynamic pressure. Given the uncertainties and risks of flying an aircraft of an unknown configuration, these investigations needed to be done within the safe bounds of a test rig while allowing sufficient freedom of motion so that the forces of flight would express the real aircraft response.

The purposes of this facility were specifically:

- to allow actual controlled full-scale flight but without the risk of take-off and landing and without requiring a flight-ready undercarriage;
- to provide thrust to the glider without requiring a flight-ready propulsion system;
- to provide a moving platform from which lift-off and touch-down could safely be done;
- to offer safety restraints in case of unexpected flight behaviour;
- to allow close observation;
- to allow upsetting the aircraft during flight to test various dynamic responses;
- to explore the tendency for pecking or pilot induced oscillation at various static margins;
- to allow flight with side-slip to test the yaw-roll coupling (dihedral effect);
- to for explore adverse yaw from roll inputs and from a roll rate;
- to allow airspeed variations to test stall speed and different trimming strategies;
- to allow pilot controlled flight for assessment of the aircraft handling qualities.

The facility also served for pilot training and as demonstrator. It had the potential to be used for thrust measurements and it could be further developed for launching by pay-out winching. The disassembled glider could be transported on the facility to the test site.

I.1 Description

A plywood platform, 3 m wide and 4 m long, was mounted onto a small pick-up truck. This deck extending ahead and beyond the sides of the vehicle served as a flow splitter plate to suppress the vertical wash of the vehicle and it served as the base from which the aircraft would take off and land. The aircraft was pulled in its centre of gravity by a trapeze towline from a bowsprit to provide the thrust for actual flight. The towline had a short portion with a bungee cord and a slack loop so that an estimate of trust could be made to give the driver a visual que of the force in the tow line. Besides the tow-line constraint, all other degrees of freedom were given, limited by safety tethers. The main pair of tethers, attached on the sides at the axis through the centre of gravity, would limit height and sideways excursions and would arrest the forward escape if the car would have to stop briskly. Roll tethers from a cross boom attached at the sweep hinges would limit roll excursions. All tethers would remain slack within a reasonable operational envelope reaching 2 m above the deck and about 1 m to either side from the centre plane. Any tether could be restrained by the operator in the back if necessary.

The rig was fitted with several spotlights for testing at night. This was useful to extend test periods given the limited availability of access to the test base. Weather conditions were also most favourable at night.

I.2 Method of Use

Besides the driver of the car and the pilot in the aircraft, two helpers stood by to provide for safe flight operations. Also a test coordinator often accompanied the team in the passenger seat. All members were in open communication with each other through an intercom system built into the helmets. The front helper operated from a lower deck with a seat in a small cut-out in the main deck in front of the windscreen. He could sit down to minimise his flow obstruction or stand up to interact with the aircraft. Standing, he would be face to face with the pilot. Through this cut-out the driver could see the helper and the thrust line. A special rear-view mirror gave the driver also a view on the aircraft. Airspeed was displayed visible to all. The front helper was always ready to pull down the nose of the glider to bring it back onto the deck if necessary, otherwise his task was to upset the glider in tests of simulated disturbances. The second helper operated from the load bay of the truck, secured by a harness. His main task was to ensure that the tethers remained slack during flight. If necessary he could arrest roll, height, sideway and forward excursions by retracting the appropriate tether. Most importantly he had to ensure that the glider would not be taken by wind while the vehicle was stationary. He would tie-down the tethers when the aircraft was not in use.

Being arranged for foot launching, the pilot stood upright with the glider fully supported from the hip-pivot of his harness, as if on a hang glider take-off ramp. As the car gained speed the pilot soon had full aerodynamic control over the wing and he could gradually fly the glider weight off the hip-belt until the glider carried itself at around 8 m/s. At about 14 m/s the weight of the pilot could also be on the wing. He could either fly the glider to lift him off his feet or he could simply retract his legs. With his toes lightly touching the deck, he had accurate feedback on the distance above the deck while looking straight ahead. The pilot then tried to keep the glider centred in the operational envelope with the wing between 3 and 5 m above the ground.

A chase car would be used to observe and to take video recordings of the experiments. It would either drive offset slightly ahead or behind the test platform.

I.3 Preliminary Tests of the Facility

Before committing the Exulans to this facility, some preliminary tests were done with a hang glider, a Fledge 2 known to have good flying qualities using steerable endplates for roll control and weight-shift for pitch control. While these tests helped to get to know and to refine the facility, they were rather discouraging because it was too difficult to keep the hang glider steady in the centre of the envelope for useful investigations. As a result, the idea of these platform tests was almost abandoned. It turned out, however, to be rather easy with the Exulans to hold a steady position within the envelope, having the benefit of responsive three-axis aerodynamic controls.

Initial tests with the Exulans had to be viewed as training exercises for the pilots and the team and to develop good procedures. Thereby, general handling qualities became known even before the systematic explorations of the flaps, the sweep system, the pitch dynamics and the lateral behaviour were performed.

Initial tests were done in calm conditions of the early morning on straight runs over the 1700 m of a taxiway of the Swartkops Air Force Base in Pretoria, South Africa. Later, with more confidence, more turbulent times of day were also found flyable, even some cross-wind could be tolerated. Eventually some tests included curved flight as the glider followed the car which was gently swerving from side to side on a 30 m wide runway. For such flights the bank angle would change at a brisk roll rate at the inversion of the track, useful for the investigation of adverse yaw.

This facility allowed actual flight as if on aero-tow by a wake-free tow plane, of course, not entirely free of flow disturbance from the vehicle. Also, the aircraft was always close to the ground, yet not within the strong influence of ground effect with the height over span more than 0.25 ($h/b > 25\%$). The pilot could have his legs hanging free or he could put the feet up on a footrest in the back of the fuselage as can be seen in the figures. In the first case the aircraft pitch inertia was essentially that of the wing. The other case, with his feet supported, pilot inertia added to that of the glider.

I.4 Typical Test Run

Once comfortable with all aspects of the aircraft, a typical test run would start with flaps in the take-off position (15° down) and the sweep angle set for slow flight (26°). Once established in flight after a brisk acceleration to the chosen airspeed (between 15 and 25 m/s) the desired settings for the test were selected. When the car slowed down at the end of the run the wings would gradually be swept forward to remain in trim with the decreasing speed. For comparison, the sweep angle would be kept the same and the elevons were pulled more and more up to remain in trim with the decreasing speed. Sometimes the flaps were also deployed for the landing. It was preferred to slow down in a way such that the glider would be in free flight, with slack in the towline and without hanging in the tethers from the rear.

I.5 Closing Remark

The full-scale flying experiences on tether were real excitement and fun and all members present of the Exulans team (most of whom at the time had no prior flying experience) had a chance to try their hand at the controls of this prototype and all managed to remain within the envelope with ease. Such a facility can serve well for pilot training with an instructor in the front.

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