Chapter 1

Introduction

The tailless swept gull-wing configuration is based on the wing shapes that exist in nature. The inboard and outboard wing sections of the gull-wing configuration have a transition in the sweep and dihedral angles.

The handling qualities of a new example of the gull-wing configuration were investigated. This gull-wing aircraft is called the Exulans. The Exulans is a research testbed that will be used to investigate the performance advantages of tailless flight by means of full-scale flight testing. Variable wing sweep, twisting elevons and all-flying winglets will be used to control the Exulans. These control devices are configured to have the minimum impact on the performance of the aircraft. The handling qualities of the swept gull-wing configuration have to be acceptable while using these different control strategies.

A performance gain can be achieved if the gull-wing configuration aircraft is designed with the CG on the so-called E-point. The Exulans is required to have inherently acceptable handling qualities with its CG positioned on this point, since no form of artificial stability augmentation will be used in its design.

The handling quality investigation was performed with analysis techniques obtained from literature. Time domain simulation techniques and frequency domain techniques were used to analyse handling qualities of the configuration. The geometry and parameters of the Exulans aircraft were used as inputs to the analyses.

1.1 The Swept Gull-Wing Configuration

The swept gull-wing configuration is defined here as a tailless configuration having a wing with a transition in the sweep and dihedral angles.

A number of design examples exist with a gull-wing configuration. The Minimoa (see Figure 1.1) is an example of a 'tailed gull-wing configuration'. The Wenk Weltensegler (see Figure 2.1) and the Nietoperz (see Figure 2.7) are examples of swept gull-wing configurations. The swept gull-wing configuration should not be confused with the plain or unswept gull-wing configuration. The plain gull-wing configuration has a wing with dihedral crank, but no significant spanwise sweep changes. Examples of this configuration are the DFS Habicht and the DFS Reiher aircraft.

The Exulans (see Section 1.2) is modern example of a tailless swept gull-wing configuration. This particular example of the configuration has forward sweep on the inboard wing, with the outboard wing section swept backwards. The inboard wing section has dihedral, while the outboard wing section has anhedral. The inboard wing section stretches from the wing root to the semi-span of the aircraft. The swept gull-wing configuration in itself is not novel, but this combination of dihedral, sweep and planform as applied to the Exulans design is unique. The handling qualities of this example of the swept gull-wing configuration will be investigated.

Figure 1.1: The Göppingen Gö 3 or 'Minimoa' (Anonymous, 2006).

1.2 The Exulans Project

The Exulans II aircraft is shown in Figure 1.2. A noteworthy feature of the Exulans is the variable sweep outboard wing (see Figure 1.3) that is used for longitudinal trim control. The pilot can control the sweep angle by means of the flight controls. The range of sweep is 20° to 36°. Variable sweep trim control has the advantage (amongst several other) that the useful range of the elevons is not reduced by trimming.

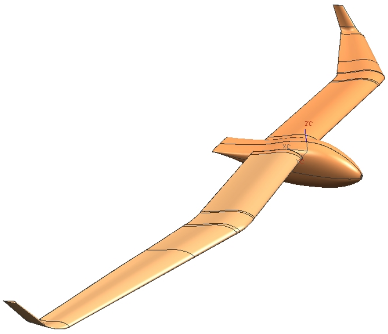


Figure 1.2: A computer generated image of the Exulans II.

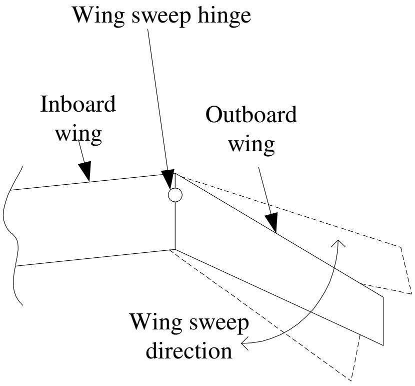


Figure 1.3: The variable outboard wing sweep as implemented on the Exulans.

The Exulans project started in 1989 as a final year project when a scale flying model was designed and built. The model was used to investigate the possible stability and control issues of the swept gull-wing configuration.

The full scale Exulans I was built following the scale prototype. The aircraft was subjected to ground tow tests and limited flight testing (see Figure 1.4). The Exulans I was designed to be a foot-launchable glider and did not have winglets. The Exulans II is designed as an ultra-light glider. It will employ all-flying winglets for directional control and yaw damping. The Exulans IIM is a possible future development that will be a motorglider.

Figure 1.4: Exulans I hanging from balloon prior to launch

The Exulans has been the research topic of a number of academic projects. The feasibility of the gull-wing configuration was investigated in the work of Huyssen (1994). Extensive research was also done on performance aspects of the Exulans glider by Crosby (1997). The architecture of a design flight simulator for the Exulans was investigated by Cronje (1999). This research was followed by another project (Agenbag, 2000) in which the flight model characterisation for the Exulans was done and applied to the simulator architecture.

1.3 The Goal

The goal of the study is the investigation of the handling qualities of a swept gull-wing configuration aircraft, specifically with the CG of the aircraft placed on or in close proximity of the E-point or the O-point. There is an aerodynamic performance gain associated with having the gull-wing configuration CG coincident with these positions.

The E-point is the centre of pressure for an elliptical circulation distribution. The O-point is similar to the E-point, but is the centre of pressure for an aircraft with winglets. Placing the CG of the aircraft on these points eliminates the need for additional trimming moments, thereby resulting in an undisturbed elliptical circulation distribution that is associated with a high Oswald efficiency.

The study was used to analyse pitch handling qualities of the Exulans at different static margins in advance of full scale flight testing. The results were used to investigate whether or not a region of static margin exists that is associated with both good handling qualities as well as high Oswald efficiency.

1.4 Methodology and Limitations

The pitch handling qualities of the tailless swept gull-wing configuration were analysed by means of the following methods and criteria:

- The C-star flying qualities criterion.

- Comparison of the gull-wing configuration pitch dynamics with other aircraft. Time domain simulations are used to make the comparison.
- Thumbprint criterion.
- Military flying qualities specifications.
- Shomber-Gertsen criterion.
- The Neal-Smith criterion.
- The Mönnich & Dalldorff criterion.
- Tumbling analysis.

The following assumptions were made in performing the handling qualities investigation:

- The investigation was restricted to the pitch handling qualities of the swept gull-wing configuration. The study of lateral handling qualities (eg. roll and yaw) is suggested as a subject for future research. This was done since many handling quality issues surrounding tailless aircraft are related to the pitch handling qualities. Pitch handling qualities are often studied in isolation because the aircraft longitudinal equations of motion can be decoupled from the lateral equations of motion. The equations can be decoupled when it is assumed that the roll rate, yaw rate and sideslip angle are zero. This approach allows the scientific study of pitch handling qualities by elimination of other variables.
- It is assumed that the aircraft has inherently favourable tip stall characteristics. Tip stall is a non-linear phenomenon that falls outside the scope of this study. Tip stall can be the cause of undesirable handling qualities, but an aircraft without tip stall problems can still exhibit poor handling qualities. As such, it needs to be studied in isolation.
- The flight simulations used as part of the analyses presented here, model only linear aerodynamics, except for non-linear drag modelling.

In the case of the gull-wing configuration only gliding flight was considered.

- All handling quality analyses presented here assume that the aircraft structure is completely rigid. The structural dynamics of the aircraft can have a large influence on the overall aircraft dynamics. This study will focus on investigating overall gull-wing configuration handling qualities, thus eliminating the variable of aeroelasticity. The structure of each aircraft is different in size and concept and therefore a separate study is required for each example of the gull-wing configuration in order to show that the aeroelastic modes of the structure do not influence handling qualities negatively. The effects of aeroelasticity on handling qualities therefore falls outside the scope of this study.

Chapter 2

A History of Tailless Aircraft

A large variety of tailless aircraft have been built in the past. The low aerodynamic pitch damping and pitch inertia give tailless aircraft unique handling qualities. This chapter is intended to provide some background on tailless aircraft designs and their handling characteristics.

A 'tailless' aircraft has no horizontal stabiliser, but can have vertical stabilisers (sometimes called 'fins', e.g. the SB-13 Arcus). An aircraft is a 'flying wing' (e.g. the Horten II) when it has no horizontal or vertical stabilisers (Nickel & Wohlfahrt, 1994:4).

One of the earliest tailless designs is the 'Weltensegler', a design by Fritz Wenk, dating back to 1921. This Weltensegler is shown in Figure 2.1. This aircraft is an early example of the swept gull-wing configuration (Huyssen, 1994).

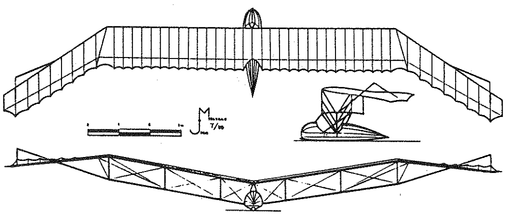


Figure 2.1: The tailless sailplane 'Weltensegler' (Nickel & Wohlfahrt, 1994:12).

Tailless aircraft aircraft technology developed rapidly during the 1930's with the designs of the Horten brothers from Germany. The two brothers produced several aircraft until the end of the Second World War. Dr. Reimar Horten continued to design and build tailless aircraft in Argentina after the War. The Horten aircraft designs have a wide variety of planform shapes. A few of the Horten aircraft are shown in Figure 2.2.

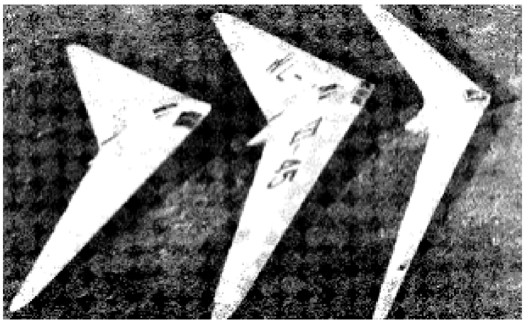


Figure 2.2: Photo of the sailplanes Horten H II, H III, H IV. (Nickel & Wohlfahrt, 1994)

Each Horten aircraft had unique flying qualities. The first Horten aircraft (H I) shown in Figure 2.3 had a triangular (strongly tapered) planform. The elevators and ailerons were not combined into an elevon in this design. The elevators were inboard, with the ailerons outboard. The H I had undesirable handling qualities. This can be attributed to the aircraft's high taper ratio, the sweepback angle of the wing and the centered elevators (Nickel & Wohlfahrt, 1994:460). The elevators in the centre of the wing caused it to have negative wash-out when deflected upwards. This can lead to wing tip stall. Alexander Lippisch, a contemporary of the Horten brothers, designed an aircraft with a very similar planform to the Horten I, the Delta I. This aircraft had the same poor handling qualities as the Horten I.

Later Horten aircraft designs improved on the flying qualities of the Horten I. These designs had larger span and aspect ratio. These aircraft combined the functions of the elevator and ailerons and the control surfaces were placed outboard spanwise. The Horten aircraft had high taper ratios. Today the high taper ratio is viewed as an undesirable design characteristic, since this can lead to tip stalling and reduced performance.

The Horten brothers experimented with various CG positions on the Hor-

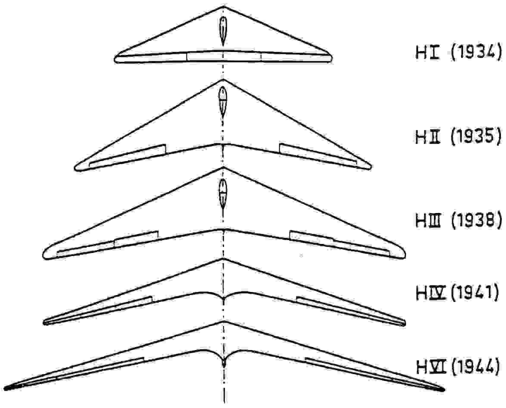


Figure 2.3: Different Horten wing planforms (Nickel & Wohlfahrt, 1994).

ten III aircraft (ibid.: 198). They found that rearward *CG* positions were associated with poor handling qualities.

The Horten IV aircraft had desirable handling qualities (ibid.: 465). The second version of this aircraft was constructed with a rearward centre of gravity and the laminar wing profile of the Mustang fighter aircraft. The design changes on the second version were made to improve performance, but instead it caused the aircraft to have unfavourable spin characteristics. These characteristics caused a flutter problem.

The Horten IX design was used as the basis of the design of the Gotha Go-229 (Horten IX) aircraft, which was designed to operate at a speed of 1000 km/h with a range of 1000 km.

The Me-163 Komet (Figure 2.4) designed by Alexander Lippisch was also a tailless design. This aircraft had acceptable handling qualities. The design had low aspect ratio and high sweepback. This gave the configuration high values of aerodynamic damping. The Me-163 flew at much higher speeds than the Horten sailplanes. This made the aerodynamic damping force of the aircraft higher.

Jack Northrop developed tailless aircraft before and after World War 2. The XB-35 and the YB-49 (Figure 2.5) bombers are examples.

Northrop engineers found through extensive testing experience that tailless designs had advantages. They have high lift and low drag characteristics,

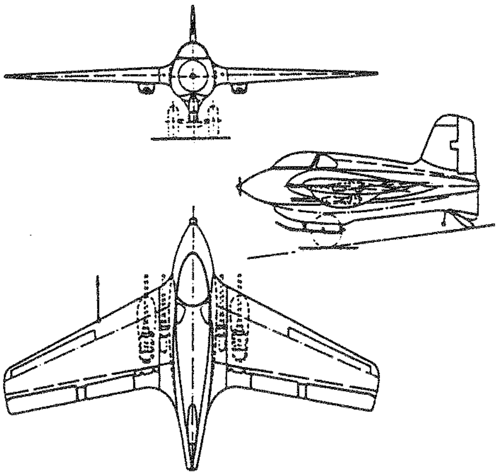
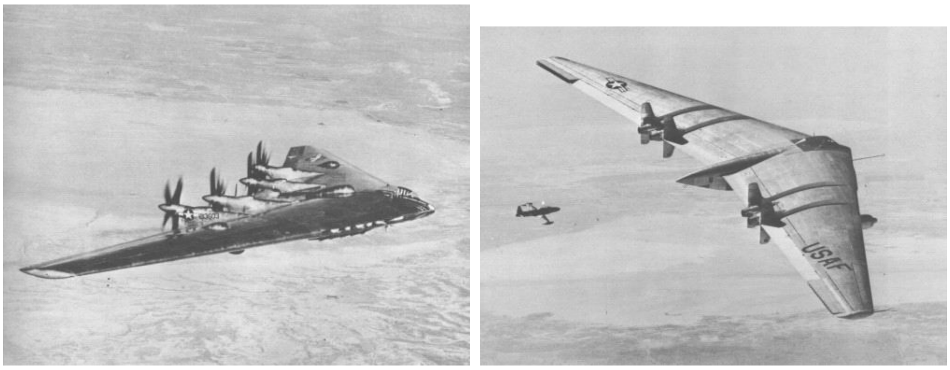


Figure 2.4: The Messerschmitt Me-163 Komet (Nickel & Wohlfahrt, 1994).

meaning that they can transport more cargo faster and farther than conventional aircraft. Structurally, the tailless aircraft is simpler to manufacture. For military usage, the smaller cross-section of the design also presented a smaller target for anti-aircraft fire. Years later the significance of smaller cross-sections became even greater as this meant smaller radar signature. This is an important part of design for stealth. The Northrop YB-49 flight test programme showed that the aircraft was not a stable enough weapons platform due to its inherent dynamics. The Northrop YB-49 displayed pitch and yaw problems that made it very slow in settling to the initial point (IP) for a bombing run. (Anonymous, n.d. a). Plans were made to fit it with an autopilot with which some of the problems could be fixed. Funding for the project was stopped before this could be done. Many factors prevented the Northrop designs from being mass produced, but these designs provided the basis for a later bomber design, namely the B-2 Spirit Stealth Bomber.

Since the designs of the Horten brothers and the Northrop company, the tailless aircraft concept has been championed by many private aircraft builders. A concise review of these designs will now be made.

Hang gliders are tailless aircraft and have been developed since the 1950's. They are not prone to the fast α oscillation known as 'pecking'. Pecking is a



(a) XB-35 (b) YB-49

Figure 2.5: Two Northrop tailless aircraft designs. (Anonymous, n.d. g)

rapid oscillatory motion around the pitch axis of the aircraft. Hang gliders are sometimes susceptible to tumbling. (Nickel & Wohlfahrt, 1994:388) Tumbling is an autorotative pitching motion primarily about an axis parallel to a vehicle's lateral axis, plus translation in a vertical plane along an inclined flight path. (Fremaux & Vairo, 1995)

The Frenchman Charles Fauvel designed and developed a range of tailless aircraft during the 50's and 60's of the twentieth century. The AV-36 is shown in Figure 2.6. This type of tailless aircraft is known as a 'flying plank'. A flying plank is a tailless aircraft with very little or no wing sweep. When such an aircraft has a rudder, it has a small lever arm between the rudder and the aircraft centre of gravity. This type of plane has been known to display α oscillations in gusty weather conditions. The frequency of the oscillations is around 0.5 Hz. Many examples of the aircraft have been built and in general it displays acceptable handling characteristics, except during take-off and landings. During landing, the aircraft's susceptibility to 'pancaking' is especially visible. Pancaking is a flight characteristic of an aircraft that occurs when the elevator is deflected upwards, resulting in a loss of lift and altitude. This is especially visible during landing in ground effect. Tailless aircraft are more susceptible to this phenomenon than aircraft with horizontal stabilisers. This is because the elevators (elevons) of tailless aircraft are on the main lifting surface and therefore the amount of lift lost due to control deflections is significant. The phenomenon appears to have the effect of an elevator reversal and is therefore sometimes incorrectly called 'control inversion'.

Figure 2.6: The Fauvel AV-36. (Anonymous, n.d. b)

A Polish design, the SZD-6x Nietoperz of the 1950's showed a forward-backward wing sweep design. The Nietoperz is a swept gull-wing configuration aircraft. Another design of the period is the SZD-20x Wampir. These designs are shown in Figure 2.7. The SZD-6x Nietoperz had poor handling qualities in gusty conditions. It displayed unpleasant pitching while flying in the turbulent wake during aerotowing operations. (Zientek, 1992) The SZD-20x Wampir also had poor gust handling qualities (worse than that of the Nietoperz). The Wampir eventually broke up in mid-air during flight testing due to aeroelastic problems.[1]

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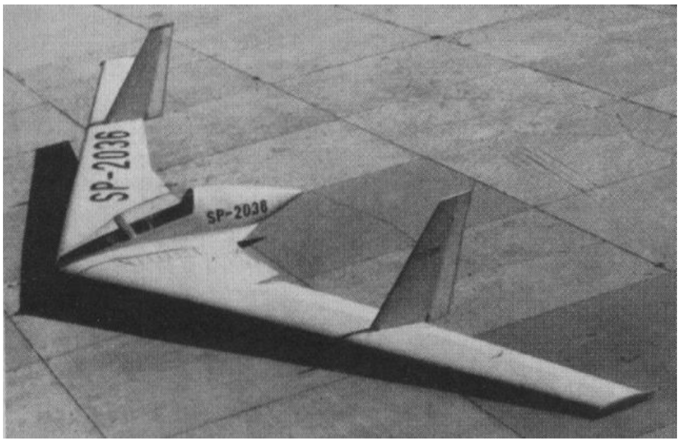
[1] The pilot survived the crash with only minor injuries since he was able to use his parachute (Zientek, 1992).

(a) Nietoperz (Anonymous, n.d. f)



(b) Wampir (Anonymous, n.d. e)

Figure 2.7: Polish tailless aircraft designs of the 50's.

The G.A.L./56 (see Figure 2.8) is a post-war tailless aircraft. It exhibited poor handling characteristics. Problems were experienced on this aircraft due to landing gear geometry and an aft centre of gravity. It had a tail heavy pitching moment near ground due to an increase in lift as a result of ground effect (Nickel & Wohlfahrt, 1994:225).

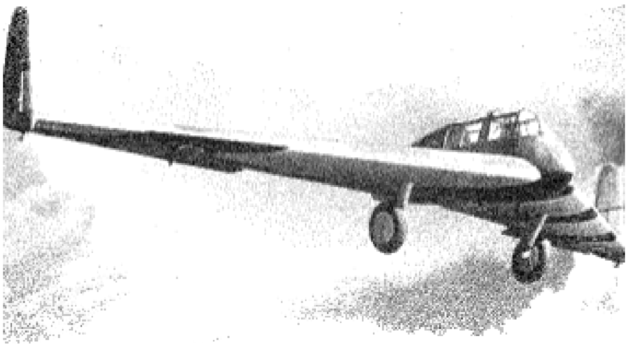


Figure 2.8: The G.A.L./56 tailless aircraft. (Nickel & Wohlfahrt, 1994:217-222)

The American Jim Marske is a leading designer of tailless aircraft in the United States. One of his designs is shown in Figure 2.9

Figure 2.9: A Jim Marske design. (Anonymous, n.d. d)

The 1980's produced the more modern low taper ratio tailless sailplanes. A number of examples of this type of aircraft exist. Most notable of these designs are the Akaflieg Braunschweig SB-13 and the Flair 30 of Günther

Rochelt. These aircraft offer improved efficiency and better handling characteristics than earlier designs. The SWIFT (Kroo et al., 1991) from the University of Stanford and the Pyxis glider (Anonymous, n.d. h) also fall in this class of tailless aircraft, see Figure 2.10.

The SB-13 had poor gust handling qualities. It is prone to 'pecking'. (Nickel & Wohlfahrt, 1994:104) The aircraft also displayed a coupling of the angle of attack oscillations with the wing bending mode. These oscillations are difficult to control since they have frequencies larger than 1 Hz, which is out of the controllable range of a human pilot.

Many modern glider designs originate from universities. The SWIFT (Figure 2.11) began as the theme of a course in aircraft design at Stanford University. This aircraft is foot-launched and combines the versatility of hang gliders with the performance of sailplanes. BrightStar gliders of California (USA) have produced a commercial version of the SWIFT aircraft called the Millennium. It folds more compactly and costs less to produce. (Kroo, 2000)

(a) Akaflieg Braunschweig's SB-13 (Nickel & Wohlfahrt, 1994)

(b) A model of the Flair 30. (Anonymous, n.d. i)

(c) The Pyxis. (Anonymous, n.d. h)

Figure 2.10: Modern low taper ratio sailplanes.

Figure 2.11: The SWIFT foot launched glider. (Kroo et al., 1991)

Tailless aircraft have seen a resurgence in the last two decades. This type of design offers many advantages such as stealth, performance improvements and structural efficiency. The advent of unmanned air vehicles (UAV's), improved control systems and the importance of stealth has again made the concept popular with designers. Aircraft such as the X-36 are a testimony to this. The X-36 has a set of redundant control effectors for increased survivability. The aircraft is made controllable by digital control systems. These control system rely heavily on an extensive aerodynamic database and modern control theory. (Calise et al., 2000)

The B-2 bomber is another example of a modern tailless aircraft. The inherent dynamics of the aircraft is masked by using digital control systems. This solves the inherent problems experienced by the earlier YB-49 design.

New passenger aircraft tailless concepts are currently being investigated with the Blended Wing Body (BWB) concept. These airliners will be more efficient[2] in carrying passengers and offer engine noise reduction advantages (Anonymous, 2005) due to the position of the propulsion system. (Figure 2.12)

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[2] The reduction of drag due to the absence of an empennage structure will lead to fuel savings. Mass is saved by integrating the passenger cabin with the wing.

Figure 2.12: The Blended Wing Body Concept from Cambridge University (Anonymous, 2005:12).

The X-43 (see Figure 2.13) is an example of a hypersonic tailless aircraft. This aircraft is to use scramjet technology in order to travel at speeds in excess of Mach 10. (Wilson, 2003)

The X-45 (see Figure 2.13) is an example of a tailless aircraft that will be used in a Joint Unmanned Combat Air System ($J - UCAS$). (Wilson, 2003) It is a UAV that is able to perform combat missions in unison with other similar UAV's. These UAV's are autonomous to a large degree.

The Boeing ScanEagle (see Figure 2.14)is an example of a tactical UAV used for reconnaissance. The current model of this aircraft has a wing span of 3 metres (10 feet). It is land or shipped launched with a pneumatic wedge catapult launcher and is recovered with a 'Skyhook' system. This system is used to land the aircraft by catching a rope hanging from a pole. (Holly, 2005) This aircraft is used to fly pre-programmed or operator initiated missions by using GPS and its onboard flight control system. This UAV was developed to be a low cost, long endurance autonomous air vehicle. As a tailless aircraft, the aircraft offers the inherent increase in aerodynamic efficiency due to reduced drag, making it suitable for long endurance missions.

(a) X-43

(b) X-45

Figure 2.13: Tailless experimental aircraft. (Wilson, 2003:23-24)

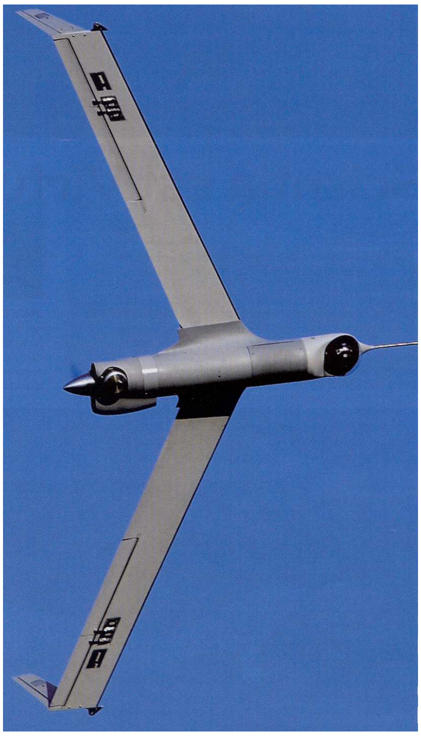

Figure 2.14: The Boeing ScanEagle *UAV* (Holly, 2005:37).

Chapter 3

Handling Quality Criteria

In order to evaluate aircraft handling qualities, it is necessary to define what constitutes good handling qualities. This chapter will present various handling quality analysis methods.

3.1 Cooper Harper Flying Qualities Rating Scale

The Cooper Harper evaluation criterion (Cooper & Harper, 1969) is a subjective method of evaluating aircraft handling qualities. This is different from all the other evaluation methods presented in this study, since the other methods are mathematical/empirical in nature. This method gives the pilot a way of having an influence on the design of the aircraft. This is important since the pilot is the end user of the aircraft.

With this method, the pilot rates the aircraft controllability on a scale from 1 to 10, with 1 being the most favourable rating. The Cooper Harper evaluation criterion is presented in Table A.1.

The Cooper Harper scale can only be used if an aircraft is available for flight testing or if an accurate flight simulator of the aircraft exists. The flight simulator should be able to simulate pitching motion as well as normal (up and down) acceleration. In addition to the hardware a group of pilots is also required in order to be able to conduct a handling qualities study.

The pilot opinion of the aircraft is then obtained by letting the various pilots either test fly the aircraft or letting the pilots interact with the the simulator. A questionnaire is then used to determine the Cooper Harper rating of the aircraft.

The Cooper Harper criterion will not be used in the gull-wing handling qualities study since neither a pitch flight simulator nor an aircraft were available for testing at the time of completion of this study.

3.2 The Zacher Protocol

The Zacher Flight Test Protocol (Thomas, 1993) was developed by Hans Zacher specifically for sailplanes and uses flight tests and a questionnaire to evaluate the flying qualities of an aircraft. This protocol was not applied to the gull-wing configuration since a prototype was not available for flight testing.

3.3 Thumbprint Criterion Analysis

The handling quality criterion presented here is based on the research presented in O'Hara (1967). An application of the thumbprint criterion can be found in Chun & Chang (2001:17). The method is based on the natural frequency and damping ratio of the aircraft dynamic modes.

The criterion is summarised in the graph presented in Figure 3.1. This graph is also known as the 'thumbprint'. An aircraft has satisfactory handling qualities when its short period damping ratio and natural frequency can be plotted in the centre of the contours of the 'thumbprint' graph.

The pilot opinion contours shown in the 'thumbprint' (Figure 3.1) were constructed from flight tests. Pilots were used to evaluate the handling qualities of so-called 'variable stability' aircraft such as the USAF/CAL T-33 aircraft. The damping ratio and natural frequencies of a variable stability aircraft can be varied by adjusting the CG of the aircraft. Pilot opinions of several CG configurations were compiled in the form of Figure 3.1. The pilot

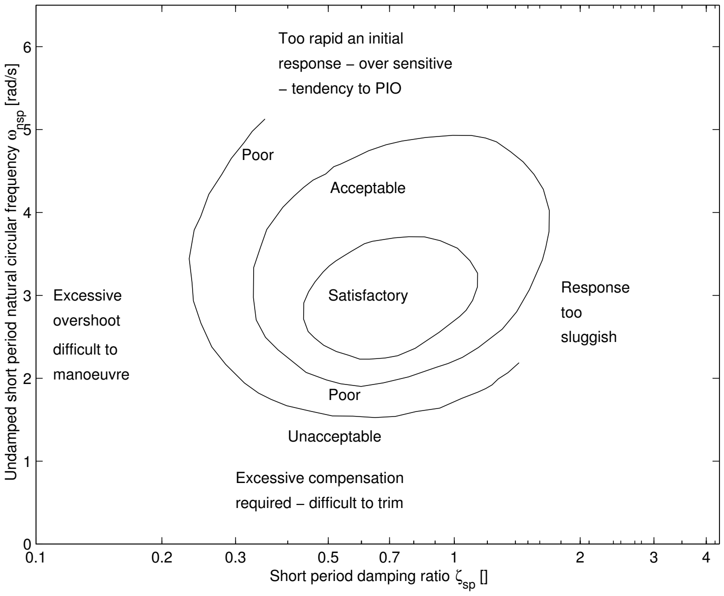

Figure 3.1: Typical pilot opinion contours for the short period mode (O'Hara, 1967).

opinions of the different configurations were expressed in pilot ratings (PR). The pilot ratings correspond to the Cooper-Harper scale. The thumbprint criterion requires two assumptions:

- The predominant variable sensed by the pilot is normal acceleration, as opposed to pitching acceleration.
- The short period response may be represented by that of a linear second order system.

The thumbprint criterion is important for aircraft that do not have stability augmentation systems. A linear second order system might not be able to approximate the dynamics of an aircraft that is stability augmented.

In order to use the thumbprint criterion, it is necessary to know the natural frequency and the damping ratio of the short period mode of an aircraft. These values may be determined by means of the following methods:

- Flight testing can be used to excite the short period aircraft mode independently of the phugoid mode. The damping ratio and natural frequency can then be established by means of curve fitting techniques from flight test data.

- A mathematical model can be created that describes the dynamics of the aircraft. This is done using equations of motion and the aerodynamic coefficients of the aircraft. These equations are usually a non-linear set of differential equations. The equations have to be linearised at a certain trim point in order to perform an eigenvalue analysis. An eigenvalue analysis is then performed on the linearised equations of the aircraft model. The eigenvalue analysis yields the short period damping ratio and natural frequency.

The thumbprint criterion analysis of the gull-wing configuration was performed by means of numerical eigenvalue analysis. The method of eigenvalue analysis as applied to the gull-wing configuration is described in Appendix B. This method was chosen as an aircraft was not available for flight testing at the time of analysis. A mathematical model of the gull-wing configuration was created (see Section 4.7). The equations of the model were linearised for a range of outboard wing sweep angles and CG positions of the gull-wing configuration. Eigenvalue analysis was performed on the linearised equations. The results of the eigenvalue analysis were plotted on thumbprint graphs like the one presented in Figure 3.1.

The thumbprint criterion is important since it is useful in determining whether an aircraft will be prone to ‘pecking’. Pecking occurs during gusty conditions or α disturbances in the case of flying wing aircraft. High and low frequency occurrences of pecking have been found (Nickel & Wohlfahrt, 1994). The SB-13 Arcus experienced pecking problems. At high static margins the aircraft displayed α oscillations of 1 to 2 Hz which pilots found difficult or impossible to control. The pecking problem improved with lower static margins because the frequency of the oscillations dropped to 0.5 to 1 Hz. The pilots of the SB-13 found it difficult to control the α oscillations because it had the same frequency as that of the human reaction (1 to 3 Hz). If the natural frequency of the α oscillations (i.e. the short period mode) were to be in the range of 0.398 to 0.637 Hz (2.5 to 4 rad/s, that falls outside the human response frequency), the pecking problem of the aircraft should be theoretically solved.

3.4 Military Flying Qualities Specifications

The military handling quality criteria are presented in MIL-F-8785C (1980). Short period mode requirements as well as phugoid mode requirements are presented in this specification.

The natural frequencies and damping ratios of the aircraft dynamic modes are used as input to this method. The values of these parameters are calculated by numerical eigenvalue analysis. The Control Anticipation Parameter or CAP is then calculated with the short period natural frequency. The value of the CAP is then plotted against short period damping ratio on the military flying qualities specifications graph. The military flying qualities specifications are graphically represented in Figure 3.2. An aircraft has the most favourable handling qualities when the aircraft's dynamic mode properties can be placed in the centre of the 'Level 1' bounding box of this figure. The phugoid damping ratio of the aircraft is compared to the requirement presented in Table 3.1.

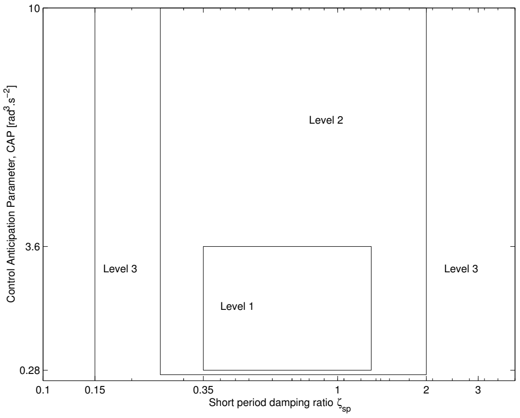

Figure 3.2: Category A control anticipation parameter and ζ_{sp} requirements (Chun & Chang, 2001).

The control anticipation parameter used in Figure 3.2 is defined in Equation 3.2. It is a function of short period natural frequency and aircraft load factor gradient (n_α). This parameter is related to the time constant of the aircraft pitch response. It is a measure of how predictable an aircraft's handling characteristics are to a human pilot. The optimum value of the CAP lies in the centre of the 'Level 1' block in Figure 3.2.

$$n_\alpha = \frac{\frac{1}{2}\rho V_T^2 S \frac{\partial C_L}{\partial \alpha}}{mg} \tag{3.1}$$

$$CAP = \frac{\omega_{n_{sp}}^2}{n_\alpha} \tag{3.2}$$

The boundaries for a Level 1 aircraft[1] and a Level 2 aircraft[2] are shown in Figure 3.2. The boxes drawn in the graphs are for the Category A flight phases[3]. The Category C flight phases[4] have the same short period damping ratio limits according to Table IV of MIL-F-8785C (1980:13), but different CAP requirements away from the optimum damping ratio/CAP point. The lower limit on the Level 1 and 2 boxes for the CAP are 0.16 and 0.096 rad^3·s^{-2} respectively for Category C[5] flight envelopes. Simply put, if an aircraft's dynamics are such that a plot of its CAP versus its short period damping ratio is a point in the centre of the 'Level 1' box of the Category A criterion, then it has optimal handling characteristics regarding Category A *as well as* Category C manoeuvres. The classifications regarding 'Level' and 'Category' are according to MIL-F-8785C (1980).

The Level 1 requirements for longitudinal manoeuvring characteristics according to MIL-F-8785C (1980:13-14) are summarised in Table 3.1. These requirements are reflected in Figure 3.2. Table 3.1 also lists a specification for the phugoid mode of the aircraft.

---

[1] Flying qualities adequate for the mission flight phase.

[2] Flying qualities adequate for the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness exists.

[3] Nonterminal flight phases generally requiring rapid manoeuvring e.g. air-to-air combat or aerobatic flying

[4] Terminal flight phases normally accomplished using gradual manoeuvres and usually requiring accurate flight-path control e.g. take-off and landing

[5] These values are 0.28 and 0.16 rad^3·s^{-2} for the Level 1 and 2 boxes respectively for Category A as shown in Figure 3.2.

Table 3.1: Level 1 requirements for MIL-F-8785C

Phugoid damping requirements	$\zeta_p \geq 0.04$
Short period damping ratio limits	$0.35 \leq \zeta_{sp} \leq 1.30$
Short period undamped natural frequency	$0.28 \leq \frac{\omega^2_{n_{sp}}}{n_\alpha} \leq 3.6\ \mathrm{rad}^3{\cdot}\mathrm{s}^{-2}$

3.5 The C-star Flying Qualities Criterion

The C-star criterion (Tobie et al., 1966) is a time-history envelope criterion. The criterion was developed by using flight test data. This criterion uses pitch rate, pitch acceleration and normal acceleration response to define desirable aircraft handling characteristics. These three responses are combined into one response by an equation. The resulting combined response is divided by the pilot stick response and then normalised by the steady state value of the response. The normalised response is then plotted on the C-star time history envelope (Figure 3.3). If the combined response falls inside the envelope, handling qualities are acceptable.

There are two C-star time history envelopes that are shown in Figure 3.3. The solid lines of the envelope represents the 'up and away' or normal manoeuvring flight envelope of favourable handling. This envelope was determined from flight tests with the F-94 variable stability aircraft. The thick dashed line represents the boundaries of favourable handling for a powered landing approach as established with flight tests from a Boeing 367-80 aircraft. If a response falls within these lines, the aircraft has a pilot opinion rating of 3.5 on the Cooper Harper scale, whether it be in the 'up and away' or the landing scenario.

The C-star criterion uses a time history envelope to evaluate handling characteristics. Aircraft step responses are used as input to the method. The C-star criterion is not 'necessary and sufficient' to evaluate handling characteristics. It is necessary to judge the aircraft response within the acceptable envelope by merit. As an example of this, the response of an aircraft may

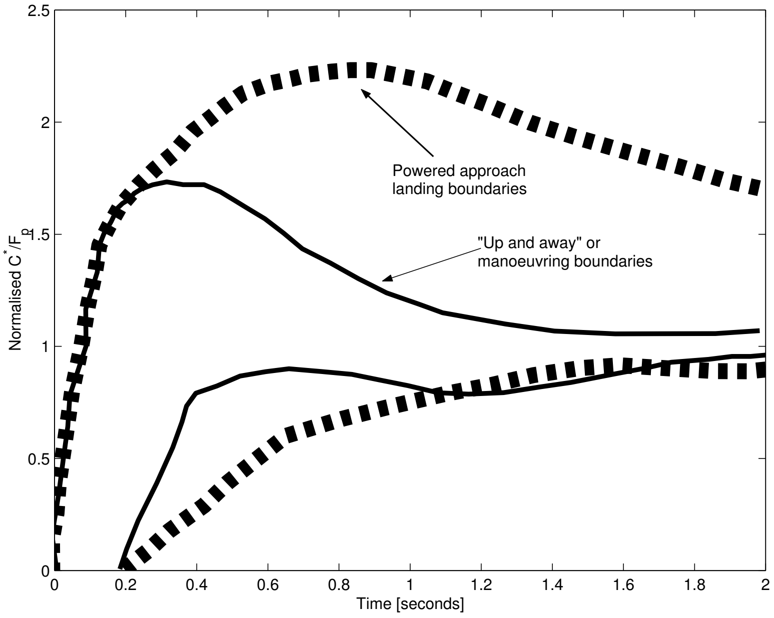

Figure 3.3: The C-star time history envelopes from Tobie et al. (1966).

fall in the acceptable boundaries of the C-star criterion, while still having a non-desirable lightly damped high frequency mode superimposed on the dominant response.

The step elevator input response required for the C-star analysis may be determined in the following two ways:

- Flight testing can be used to measure the step response of an aircraft.
- Flight simulation may be used to obtain the step response. This approach was used to analyse the gull-wing configuration aircraft.

The C-star method is useful when evaluating a stability augmented aircraft because the lumped dynamics of the airframe and the control system are evaluated. The C-star criterion is a time domain method. It shows the influence of numerator dynamics (zeros dynamics) and non-linear effects on handling qualities. Tobie et al. (1966:95) states that aircraft pitch motion cues are very important with respect to handling qualities. The 'thumbprint' criterion does not take into account these motion cues.

The C-star response is calculated by combining the normal acceleration with the pitch acceleration that is sensed by the pilot. The pilot's position is not at the centre of gravity of the aircraft (for the majority of designs) and therefore he or she will experience increased acceleration levels compared to those of the centre of gravity. The additional acceleration due to pitching has to be calculated at the position of the pilot's head, since this is where the sensory organs are located. The following formula is used to combine normal acceleration and pitch acceleration and pitch rate:

$$C^* = K_1 n + K_2 \dot{\theta} + K_3 \ddot{\theta} \tag{3.3}$$

where the value of K_1 is 1 (dimensionless) and K_2 equals 12.4 (units of [seconds]) as derived in Tobie et al. (1966:96). The 'n' parameter is the normal acceleration of the aircraft in g's. $\dot{\theta}$ and $\ddot{\theta}$ are the pitch rate (in rad/s) and pitch acceleration (rad/s^2) respectively of the aircraft. l is positive when the pilot is situated in front of the CG and negative when the pilot is situated behind the CG. The K_3 constant is calculated with the following equation:

$$K_3 = \frac{l}{g} \tag{3.4}$$

The l parameter is the distance from the pilot's station to the centre of gravity of the aircraft and g is gravitational acceleration. K_3 has the units of [seconds^2]. The pilot of the Exulans does not sit upright as with most aircraft, but lies in the prone position as with a hang glider. The Exulans is used here as an example of a gull-wing configuration , but this does not imply that all gull-wing configurations will have the pilot in the prone position. For the Exulans, l is calculated as the sum of the distance from the aircraft centre of gravity to the hips of the pilot and the distance from the hips to the eyes. The last mentioned distance (884 mm) was obtained from Anonymous (1997) for a 97'th percentile UK aircrew male.

The C-star response calculated with Equation 3.3 is divided by the pilot stick input force or F_s. This is done in order to plot the response on Figure 3.3. Neal & Smith (1970) presents a pilot handling qualities study where the C-star method is also illustrated. The examples from this reference calculate stick force with a linear stick force gradient. Neal & Smith (1970:18) indicates that favourable handling qualities correspond to a stick force gradient of 20 to 31 N/g. A value of 25.5 N/g was chosen for use in the gull-wing configuration C-star analysis. The arbitrary value was used since the actual gearing of the aircraft was not known at the completion of this study.

The step responses presented in Section I.1 were used in the evaluation of the Exulans.

3.6 The Shomber-Gertsen criterion

This evaluation criterion was proposed in Shomber & Gertsen (1967). This article presents pilot opinion contours that are based on the zeros of the elevator input to pitch response transfer function. The work of Shomber & Gertsen (1967) is also closely related to the fixed base simulator study performed by Chalk (1963).

The transfer function of Equation 3.5 is the basis of the zeros criterion of Shomber & Gertsen (1967). The zero of this transfer function is influential in the handling qualities of the aircraft because it influences the phase and magnitude of the aircraft pitch response. The zeros of the elevator input to pitch response transfer function varies with airspeed. As a result, the method is useful in determining how handling qualities vary at different airspeeds. The relationship of pilot opinion to different flight conditions was set up using flight test data and fixed base simulator studies.

$$\frac{q(s)}{\delta_e(s)} = \frac{K_q(1+\tau_{\theta_2}s)}{\frac{s^2}{\omega_{n_{sp}}^2}+\frac{2\zeta_{sp}}{\omega_{n_{sp}}}s+1} \tag{3.5}$$

The Shomber-Gertsen handling qualities analysis entails the calculation of the values of the following parameters for an aircraft at a given operating condition (trim speed): n_α, $\omega_{n_{sp}}$, ζ_{sp} and $1/(\tau_{\theta_2}\omega_{n_{sp}})$. These parameter values are then plotted on Figures 3.4 or 3.5. If $n_\alpha \leq 15$ g/rad, the values are plotted on Figure 3.4, otherwise the values are plotted on Figure 3.5. The closer the plotted point is to the 'Satisfactory' region, the better the handling qualities. The zeros rating method is related to the Cooper Harper rating scale. Figures 3.4 and 3.5 have iso pilot rating contours that are related to the Cooper-Harper scale.

The natural frequencies and damping ratios of the aircraft modes required for this method are calculated by means of numerical eigenvalue analysis.

The $1/\tau_{\theta_2}$ parameter can be approximated by L_α. This is true when the longitudinal control surface located aft of the centre of gravity exhibits negligible control surface lift (Shomber & Gertsen, 1967):

$$\frac{1}{\tau_{\theta_2}} = \frac{L_\alpha - M_\alpha(L_{\delta_e}/M_\delta)}{1 - M_{\dot{\alpha}}(L_{\delta_e}/M_\delta)} \approx L_\alpha \tag{3.6}$$

For a tailless aircraft, control surface lift is not negligible because the elevon is on the main wing of the aircraft. The elevon is also close to the centre of gravity of the aircraft. The full expression must therefore be used to calculate $1/(\tau_{\theta_2}\omega_{n_{sp}})$ when evaluating the handling characteristics of a tailless aircraft such as the gull-wing configuration. Even though Figure 3.4 shows $L_\alpha/\omega_{n_{sp}}$ appearing on the y-axis, the value of $1/(\tau_{\theta_2}\omega_{n_{sp}})$ will be used to plot the y-coordinate of the values on this graph, since the gull-wing configuration is tailless.

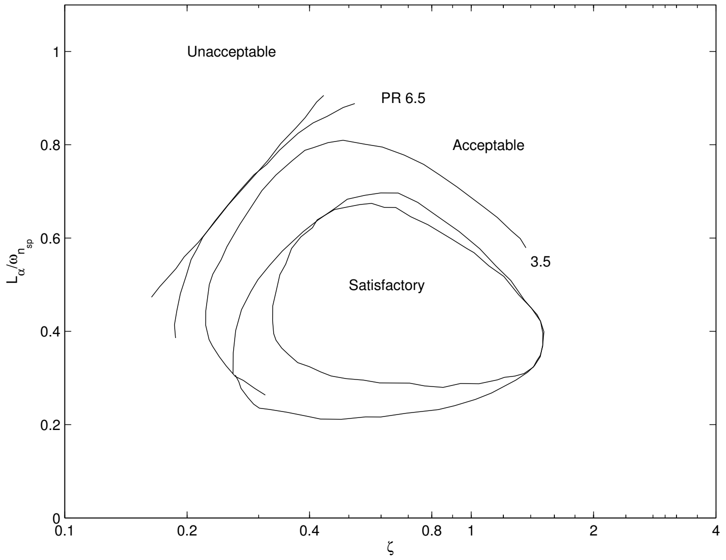

Figure 3.4: The longitudinal short-period criterion of Shomber & Gertsen (1967) for $n_\alpha \leq 15$ g/rad.

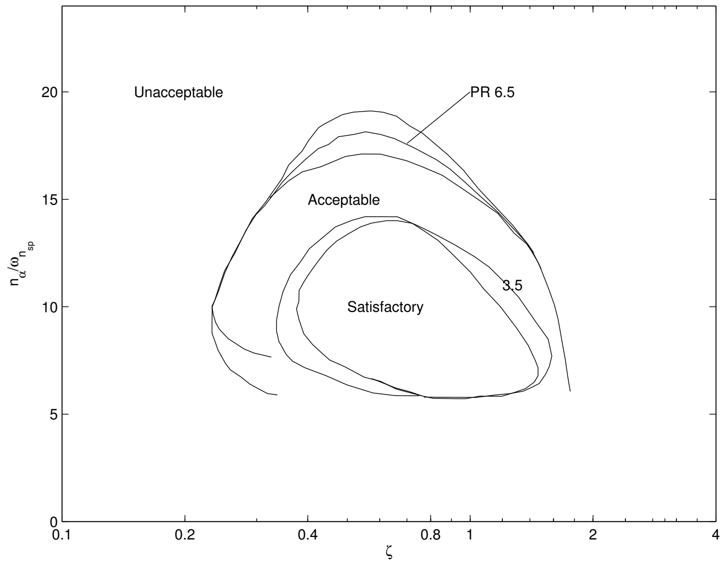

Figure 3.5: The longitudinal short-period criterion of Shomber & Gertsen (1967) for $n_\alpha \geq 15$ g/rad.

n_α (Equation 3.7) is the incremental load factor per unit angle of attack. This parameter is varied by changing the trim airspeed of the aircraft, since the other variables of this parameter (e.g. mass, wing area, lift curve slope) are constants.

$$n_\alpha = \frac{\frac{1}{2}\rho V^2 S C_{L_\alpha}}{mg} \tag{3.7}$$

3.7 The Neal-Smith Criterion

The Neal-Smith aircraft handling quality evaluation method was originally developed in order to assess the handling qualities of fighter aircraft equipped with flight control systems (Neal & Smith, 1970). The method requires a pilot transfer function model and an aircraft pitch attitude to stick force transfer function. This is used to quantitatively evaluate the amount of compensation that a pilot needs to make in order to control the aircraft. The result of the evaluation is then plotted on an opinion chart that was created using flight test data and pilot opinion. This chart is presented in Figure 3.6.

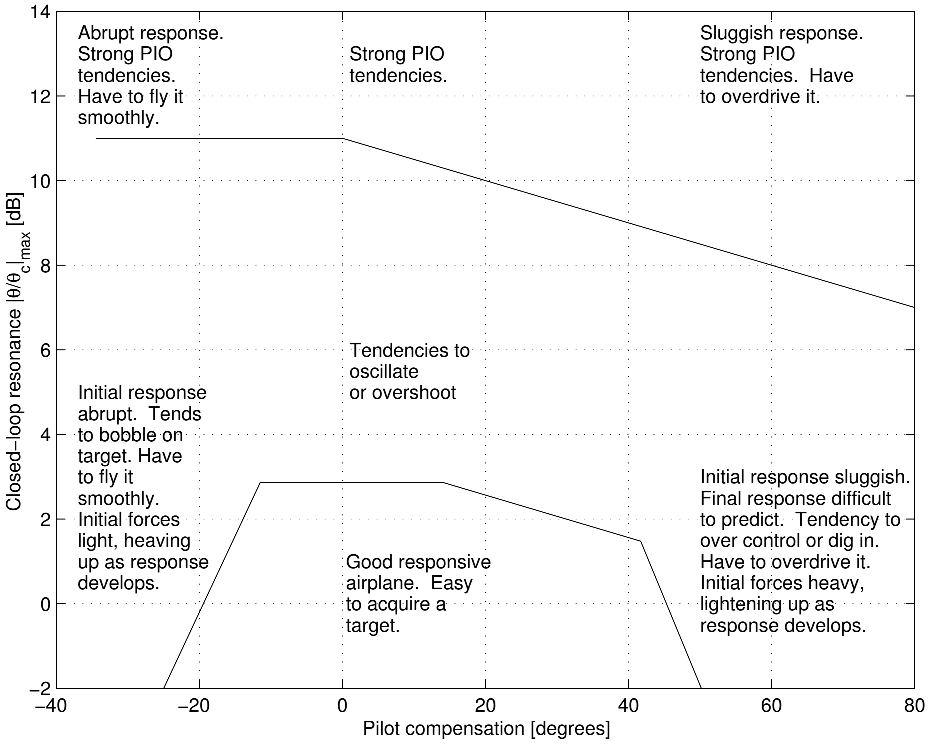

Figure 3.6: The Neal-Smith criterion for fighter manoeuvring dynamics.

The Neal-Smith evaluation criterion can also be applied to an aircraft without a flight control system. This was the case with the gull-wing configuration, since the inherent controllability (without a control system) of the aircraft was investigated. The control system dynamics were simply omitted in the aircraft transfer function in order to accommodate this type of aircraft.

The transfer function model of the pilot and the aircraft was obtained from Neal & Smith (1970:38). The pilot model ($\frac{F_s}{\theta_e}$) is presented in the following equation:

$$\frac{F_s}{\theta_e} = K_p e^{-0.3s} \frac{\tau_{p1} s + 1}{\tau_{p2} s + 1} \tag{3.8}$$

This type of model is known as a compensatory tracking model. It includes a time delay as well as lead and lag compensation and a gain. The time delay models the neuromuscular lag of a human pilot. Neal & Smith (1970) indicates that the time delay may vary between 0.2 and 0.4 seconds. The value of 0.3 seconds was used in the analysis of the gull-wing configuration.

The unaugmented aircraft model (derivation is shown in Appendix L) that was used to model the pitch dynamics of the gull-wing configuration is presented in the following equation:

$$\frac{\theta}{F_s} = \frac{K_\theta(\tau_{\theta_2} s + 1)}{s(\frac{s^2}{\omega_{nsp}^2} + \frac{2\zeta_{sp}}{\omega_{nsp}} s + 1)} \tag{3.9}$$

where the airframe gain K_θ is:

$$K_\theta = \frac{g}{V_T (F_s/n)_{SS}} \tag{3.10}$$

$\frac{F_s}{n}_{SS}$ will eventually be determined by means of flight test when the Exulans is built and flown. A $\frac{F_s}{n}_{SS}$ value of 25.5 N/g was used in the analysis presented here. This value was chosen because flight test pilots of the Neal-Smith evaluation programme found the most favourite gradients to lie between 20 and 31 N/g. (Neal & Smith, 1970:18)

The following transfer function and 'open loop' and 'closed-loop' definitions are important to understand the Neal-Smith method. These definitions are taken from Neal & Smith (1970:39).

$\frac{\theta}{F_s}$ is the *open-loop* transfer function of the aircraft plus control system. In the case of the gull-wing configuration this would refer to the aircraft transfer function alone because the aircraft is analysed without a flight control system.

$\frac{\theta}{\theta_e}$ is the *open-loop* transfer function of the aircraft, control system and pilot.

$\frac{\theta}{\theta_c}$ is the *closed-loop* transfer function of the aircraft, control system and pilot.

The terms 'open-loop' and 'closed-loop' are meant to apply to the block diagram shown in Figure 3.7.

The following definitions are also important:

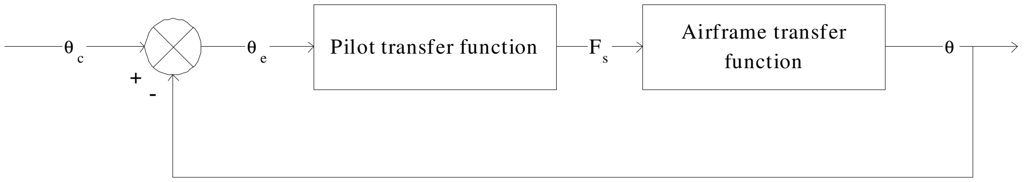

Figure 3.7: Mathematical model of pitch attitude tracking.

Bandwidth (BW): Bandwidth is defined as the frequency for which the closed-loop Bode phase, $\angle(\frac{\theta}{\theta_c})$, is equal to -90 degrees. In the context of fighter design, it is a measure of how quickly the pilot can move the aircraft's nose toward the target.

Droop Droop is defined as the maximum excursion of the closed-loop Bode amplitude, $|\frac{\theta}{\theta_c}|$, below the 0 dB line for frequencies less than BW (see Figure 3.8). Once again, in the context of fighter design and in the absence of large oscillations, droop is a measure of how slowly the nose settles down on a target.

Standard of Performance A minimum bandwidth, $(\text{BW})_{min}$, of 3.5 rad/s, and a maximum droop of 3 dB: For frequencies of ω less than 3.5, $\angle(\frac{\theta}{\theta_c})$ must be greater than -90 degrees and the $|\frac{\theta}{\theta_c}|$ must be greater than -3 dB.

PIO Tendency The tendency to oscillate or *PIO* is defined in terms of the Bode magnitude of any closed-loop resonant peak, $|\frac{\theta}{\theta_c}|_{max}$, that results from the pilot's efforts to achieve the performance standards. This standard of performance was developed using the flight test data and pilot opinion of the fixed base instrument flight rules (IFR) simulator tests that are documented in the work of Neal & Smith (1970).

Pilot Compensation The pilot's physical and mental workload required to achieve the standard of performance is defined in terms of the phase of his compensation at ω =(BW)$_{min}$:

$$\angle_{pc} = \angle\left(\frac{i\omega\tau_{p_1} + 1}{i\omega\tau_{p_2} + 1}\right) \tag{3.11}$$

Maximum closed loop resonance This resonant peak ($|\frac{\theta}{\theta_c}|_{max}$) is shown and graphically defined in Figure 3.8.

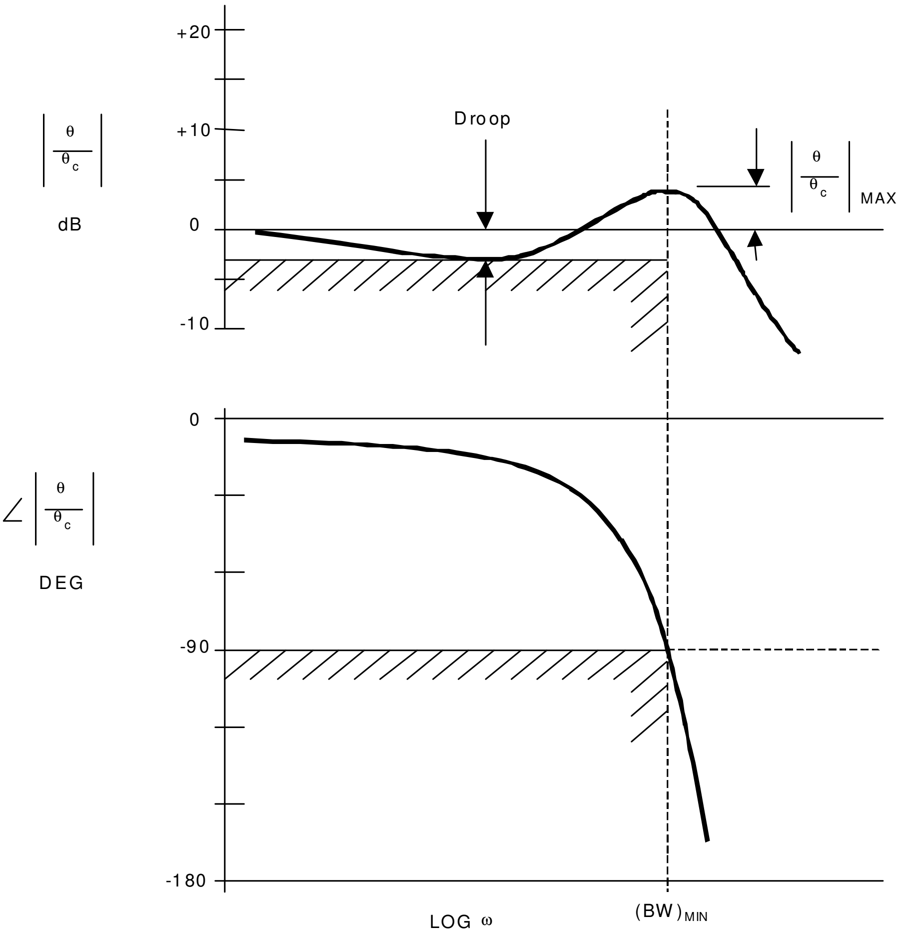

Figure 3.8: Tracking performance standards used in the Neal-Smith analysis(Neal & Smith, 1970:44).

The way the Neal-Smith method was applied in this work is summarized as follows:

1. The Bode amplitude and phase characteristics of the aircraft's pitch attitude response to stick-force inputs ($|\frac{\theta(i\omega)}{F_s(i\omega)}|$ and $\angle\frac{\theta(i\omega)}{F_s(i\omega)}$) have to be obtained. The amplitude and phase characteristics for the gull-wing configuration were obtained using the $\frac{\theta}{F_s}$ transfer function together with the aerodynamic coefficients presented in Chapter 4, but the characteristics may also be measured during flight testing. The frequency range of interest according to the Neal-Smith report is from 0.5 rad/s to at least 10 rad/s.

2. The open-loop Bode amplitude and phase characteristics for the aircraft and the pilot delay is then calculated at some nominal value of K_p (e.g. 1.0). The superscript asterisk signifies that the uncompensated pilot, i.e. only the pilot gain and time delay is modelled in the transfer function.
$$\left(\frac{\theta}{\theta_e}\right)^* = 1.0 \times e^{-0.3s}\left[\frac{\theta}{F_s}\right] \tag{3.12}$$

3. $|\frac{\theta}{\theta_e}|^*$ is then plotted versus $\angle\frac{\theta}{\theta_e}^*$ and overlaid on a Nichols chart. The resulting curve is then translated until the performance standards of Figure 3.8 are just met.

4. If $|\frac{\theta}{\theta_c}|_{max}$ is greater than 0 dB, then pilot compensation is required. The compensation can be determined by adding the amplitude and phase of Figure 3.10 to the uncompensated amplitude-phase curve, for several trial values of τ_{p_1} or $\frac{\tau_{p2}}{\tau_{p_1}}$. The value of τ_{p_1} or $\frac{\tau_{p2}}{\tau_{p_1}}$ that results in the smallest value of $|\frac{\theta}{\theta_c}|_{max}$ will be that which causes the bandwidth to exactly equal 3.5 rad/s and the maximum droop to exactly equal 3 dB.

5. $|\frac{\theta}{\theta_c}|_{max}$ is then obtained from Figure 3.9 and $\angle_{pc}$ is read directly from Figure 3.10 (for $\omega = 3.5$ and the particular value of τ_{p_1} or $\frac{\tau_{p2}}{\tau_{p_1}}$ used.)

6. The values of pilot compensation ($\angle_{pc}$) and closed loop resonance ($|\frac{\theta}{\theta_c}|_{max}$) are then plotted on the opinion chart of Figure 3.6. The handling qualities of the aircraft are then determined from the opinion chart. The lower line on this figure represents a Pilot Rating (PR) of 3.5, while the

top line represents a Pilot Rating of 6.5. The term Pilot Rating refers to the evaluation rating of the Cooper-Harper scale (see Section 3.1.)

The performance standards of the Neal-Smith method (Figure 3.8) are represented on a Nichols chart in Figure 51 of Neal & Smith (1970). This Nichols chart is presented in Figure 3.9.

The amplitude-phase curves for 'optimum' pilot compensation is presented in Figure 52 of Neal & Smith (1970). This graph is presented in Figure 3.10.

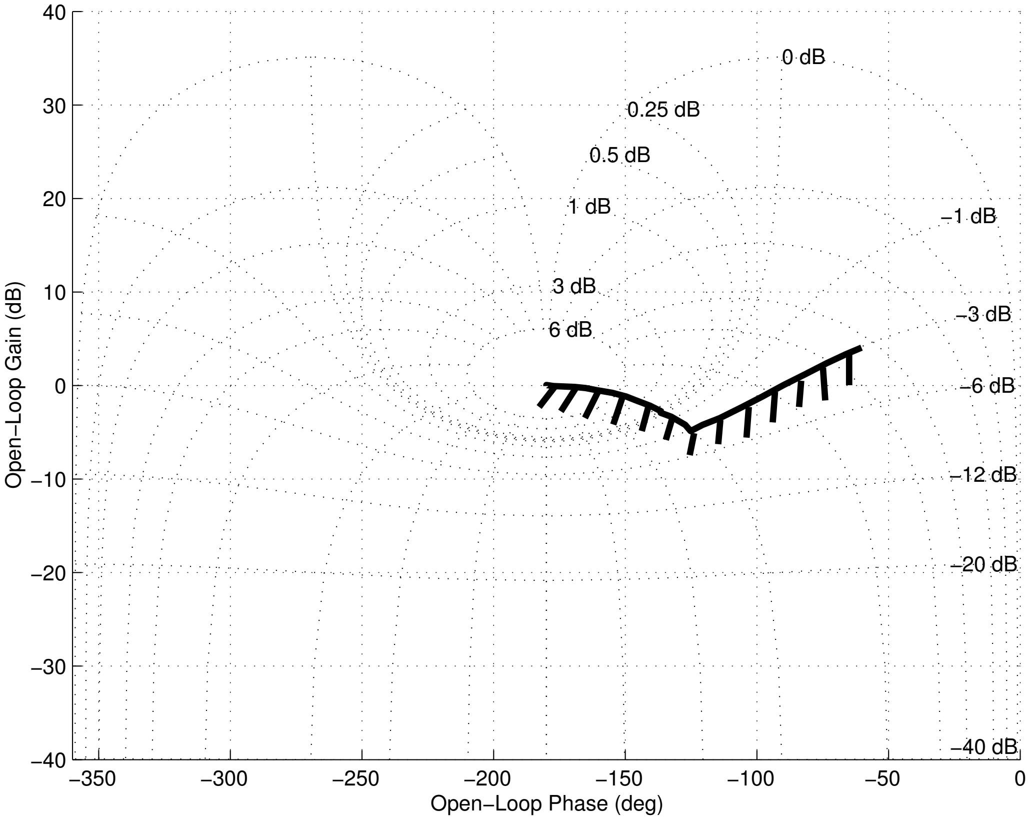

Figure 3.9: Nichols chart with performance standards.

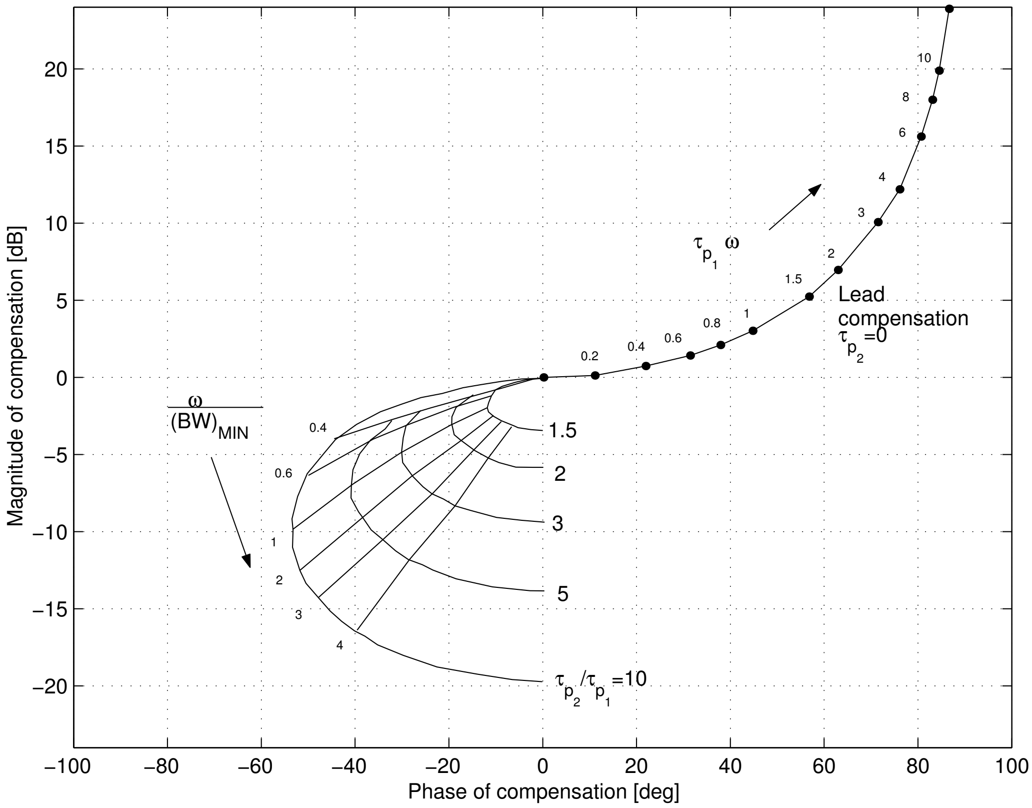

Figure 3.10: Amplitude-phase curves for 'Optimum' pilot compensation. (Neal & Smith, 1970:54)

3.8 A Turbulence Handling Criterion

The previous paragraphs covered handling quality investigation methods that may be applied to any type of aircraft. Tailless aircraft have unique handling quality issues in turbulent atmospheric conditions as a result of their low damping and low pitch inertia.

The inequality shown in Equation 3.13 (Mönnich & Dalldorff, 1993) has been presented as a handling quality criterion for tailless aircraft in turbulent conditions. If the inequality is true, good flying qualities can be expected of an aircraft in turbulent conditions. For most tailed aircraft this inequality would be true. Tailless aircraft usually have low aerodynamic pitch damping when compared to tailed aircraft. This means that the value of C_{M_q} is usually sufficiently low for tailless aircraft that the inequality of Equation 3.13 becomes false.

$$\frac{C_{M_\alpha}}{C_{M_q}} < (C_{L_\alpha} + C_{D_e})\frac{\rho S \bar{c}}{2m} \tag{3.13}$$

The only requirement for applying this criterion is that the aerodynamic coefficients, the mass (m), wing area (S) and mean aerodynamic chord ($\bar{c}$) of the aircraft be known. It is also required to know the density altitude (ρ) at which the aircraft will operate. The aerodynamic parameters include the pitch damping coefficient (C_{M_q}), the moment curve slope (C_{M_α}), the lift curve slope (C_{L_α}) and the equilibrium drag coefficient (C_{D_e}). The values for these parameters are then simply substituted into Equation 3.13 to evaluate the inequality relationship of the criterion.