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Longitudinal handling characteristics of a tailless gull-wing aircraft

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by

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Synopsis

Longitudinal handling characteristics of a tailless gull-wing aircraft

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A handling quality investigation was performed on the swept gull-wing configuration. The swept gull-wing configuration is tailless and has a wing with a transition in the sweep and dihedral angle. An example of this type of aircraft is the Exulans. This aircraft is currently under development at the University of Pretoria. The handling quality study was focussed on pitch axis dynamics. The Exulans is a research testbed that will be used to investigate the swept gull-wing configuration and its special controls by means of full-scale flight testing. Variable wing sweep, twisting elevons and winglets will be investigated as means of control. These control devices are configured in such a way as to have 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.

The study was launched to investigate whether a gull-wing configuration aircraft will have satisfactory handling qualities at CG positions associated with the most favourable aerodynamic performance. There is an aerodynamic performance gain in designing an aircraft so that the CG falls on the so-called 'E-point'. The E-point is the centre of pressure for an elliptical circulation distribution. An elliptical circulation distribution is associated with the highest Oswald efficiency for an aircraft.

Time domain simulation techniques and frequency domain analysis techniques were used to analyse the handling qualities of the gull-wing configuration. The C-star criterion was used to analyse handling qualities with time domain simulation data as input. Comparative time domain simulations were performed between the Exulans and other aircraft to compare handling qualities. Eigenvalue analysis was used together with the thumbprint criterion to investigate inherent gull-wing airframe dynamics. The Shomber-Gertsen and Military Specification 8785 criteria were also used for the same purpose. The Neal-Smith method was used to investigate the effect of control authority on handling qualities and the effect of a pilot. The Mönnich and Dalldorff criterion was used to evaluate gust handling qualities. An analysis chart by Fremaux and Vairo was used to evaluate the tumbling susceptibility of the gull-wing configuration.

The pitch handling quality investigation shows sufficient promise that the swept gull-wing configuration will have acceptable handling qualities with the CG placed at positions associated with optimised aerodynamic performance. Analysis showed that the swept gull-wing configuration is potentially prone to tumbling. With low static margins, the configuration should exhibit improved handling qualities in gusty conditions when compared to existing tailless aircraft.

It is recommended that a lateral handling quality study be performed before full scale flight testing commences on the Exulans. In addition, the possibility of wingtip stall must be investigated for the case of the swept gull-wing configuration.

KEYWORDS: Tailless aircraft; Handling qualities; Gust handling qualities; E-point; O-point; Flight simulation; Swept gull-wing configuration; Mönnich and Dalldorff criterion; C-star criterion; Thumbprint criterion; Shomber-Gertsen analysis; Neal-Smith analysis; Pilot induced oscillation; Pecking; Tumbling; Exulans; Variable static margin; Variable sweep wing; Pilot mathematical model; Oswald efficiency.

Opsomming

Longitudinale hanteringseienskappe van 'n stertlose meeuvlerkvliegtuig

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'n Ondersoek is geloods aangaande die vlughanteringseienskappe van die meeuvlerkuitleg. Hierdie uitleg is 'n stertlose ontwerp waarvan die vlerk 'n oorgang in veeg en diëderhoek het. Die Exulans sweeftuig, tans onder ontwikkeling by die Universiteit van Pretoria, is 'n voorbeeld van hierdie uitleg. Die studie het gefokus op heivlak dinamika. Die Exulans is 'n navorsingsplatform wat gebruik sal word om die spesiale vlugbeheerstelsel van die meeuvlerkuitleg te ondersoek deur volskaalse vlugtoetse. Veranderbare vlerkveeg, asook wringbare hoogterolroere en rigtingroere op entvlerke word gebruik om die Exulans te stuur. Die beheeroppervlaktes is ontwerp om die impak op die werksverrigting van die vliegtuig te minimeer. Die hanteringseienskappe van die meeuvlerkuitleg moet aanvaarbaar wees met die gebruik van hierdie stuurmeganismes.

Die ondersoek moes bepaal of die meeuvlerkuitleg gunstige hanteringseienskappe sal vertoon terwyl die vliegtuig se swaartepunt geplaas is op 'n posisie wat assosieer word met die mees gunstige aerodinamiese werksverrigting. Daar is 'n voordeel met betrekking tot aerodinamiese werksverrigting wanneer 'n vliegtuig ontwerp word sodat die swaartepunt ooreenstem met die sogenaamde 'E-punt'.

Die E-punt is die sentroïede van die drukverdeling van 'n elliptiese sirkulasieverspreiding. 'n Elliptiese sirkulasieverspreiding word assosieer met die mees gunstige Oswald rendement van 'n vliegtuig.

Tyddomein simulasietegnieke en frekwensiedomein analises is gebruik om die hanteringseienskappe van die meeuvlerkuitleg te ondersoek. Die C-ster kriterium is gebruik om hanteringseienskappe te ondersoek met behulp van tyddomein simulasie resultate. Tyddomein simulasies was gebruik om die Exulans en ander vliegtuie te vergelyk met betrekking tot hanteringseienskappe. Eiewaarde analise is gebruik tesame met die 'vingerafdruk' kriterium om die inherente lugraamhanteringseienskappe van die meeuvlerk te ondersoek. Die Shomber-Gertsen en Militêre Standaard 8785 kriteria is ook vir dieselfde doel gebruik. Die Neal-Smith metode is gebruik om die effek van beheeroutoriteit op hanteringseienskappe en die invloed van 'n vlieënier te ondersoek. Die Mönnich-Dalldorff kriterium is gebruik om die effek van rukwindtoestande op hanteringseienskappe te ondersoek. 'n Analisekaart deur Fremaux en Vairo is gebruik om die vatbaarheid van die meeuvlerkuitleg vir tuimeling te ondersoek.

Die heivlak hanteringseienskapstudie het getoon dat die meeuvlerkuitleg genoegsame belofte van gunstige hanteringseienskappe toon wanneer die swaartepunt geplaas word op posisies wat assosieer word met hoë aerodinamiese werksverrigting. Analise het ook onthul dat die meevlerkuitleg vatbaar is vir tuimeling. Die studie het verder ook aangetoon dat die uitleg meer gunstige hanteringseienskappe het as bestaande stertlose ontwerpe tydens turbulente omstandighede, mits dit met 'n lae stabiliteitsgrens ontwerp word.

Dit word aanbeveel dat 'n laterale hanteringseienskapstudie van stapel gestuur word voor enige volskaalse vlugtoetse met die Exulans onderneem word. Die moontlikheid van staking by die vlerkpunte moet ook ondersoek word vir die meeuvlerkuitleg.

SLEUTELWOORDE: Stertlose vliegtuig; Hanteringseienskappe; E-punt; O-punt; Vlugsimulasie; Teruggeveegde meeuvlerkkonfigurasie; Mönnich en Dalldorff kriterium; C-ster kriterium; Vingerafdruk kriterium; Shomber-Gertsen analise; Neal-Smith analise; Vlieënierinsetossilasies; Knikossilasies; Tuimelvlug; Exulans; Veranderbare stabiliteitsgrens; Veranderbare vlerkveeghoek; Oswald rendement.

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Artificial flight may be defined as that form of aviation in which a man flies at will **in any direction**, by means of an apparatus attached to his body, the use of which requires **dexterity** of the user.

Otto Lilienthal, 1895

Kunstflug bedeutet willkürliches Fliegen eines Menschen mittels eines an seinem Körper befestigten Flugapparates, dessen Gebrauch persönliche geschicklichkeit voraussetzt.

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Nomenclature

Mathematical Symbols

A	Linearised state space matrix (see Equation B.6)
A	Wing area (Only Figure E.1) [m^2]
a_0	Section lift curve slope for a section normal to the quarter-chord line when placed in the direction of the free stream [/rad]
b	Wing span of aircraft [m]
$\bar{c}$	Mean aerodynamic chord [m]
c	Damping term matrix of a multi-degree-of-freedom system
C^*	C-star response []
C_D	Aircraft drag coefficient
C_L	Aircraft lift coefficient
C_M	Aircraft moment coefficient
C_{D_0}	Parasitic drag coefficient
C_{D_α}	Drag coefficient derivative w.r.t. angle of attack
C_{D_e}	Equilibrium drag coefficient
C_{D_i}	Coefficient of induced drag
C_{D_V}	Drag coefficient derivative w.r.t. true airspeed

$C_{D_{\delta_e}}$ Drag coefficient derivative w.r.t. angle of elevator (or elevon) deflection

C_{L_0} y-intercept of lift coefficient curve

C_{L_q} Lift coefficient due to the pitch rate of the aircraft

C_{L_V} Lift coefficient derivative w.r.t. true airspeed

C_{L_α} Lift coefficient curve slope [/rad]

$C_{L_{\delta_e}}$ Lift coefficient due to the elevator (or elevon) deflection

$C_{L_{\dot{\alpha}}}$ Lift coefficient derivative w.r.t. the rate of change of angle of attack

C_{M_0} y-intercept of moment curve

C_{M_q} Pitch moment coefficient of aircraft due to pitch rate, or pitch damping [/rad]

C_{M_V} Moment coefficient derivative w.r.t. true airspeed

C_{M_α} Moment coefficient curve slope of the aircraft [/rad]

$C_{M_{\dot{\alpha}}}$ Pitch moment coefficient of aircraft due to rate of change of angle of attack. This coefficient relates to aerodynamic damping due to the interaction between the forward lifting surface and aft lifting surface (the horizontal stabiliser for most aircraft). [/rad]

$C_{M_{\delta_e}}$ Change of moment coefficient w.r.t. elevon deflection angle [/rad]

d Time delay

e Oswald's span efficiency factor

$\overline{F}$ Excitation force vector of a multi-degree-of-freedom system

F_s Elevator (or elevon) stick force, positive for pull [N]

g Gravitational acceleration [m/s^2]

I Identity matrix

i The complex part of a complex number

I_{xx} X-X moment of inertia (aircraft body axis system) [kg·m^2]

I_{yy} Y-Y moment of inertia (aircraft body axis system) [kg·m^2]

I_{zz} Z-Z moment of inertia (aircraft body axis system) [kg·m^2]

k Stiffness matrix of a multi-degree-of-freedom system

K_1 Normal acceleration scaling constant of the C* analysis [].

K_2 Pitch rate scaling constant of the C* analysis [seconds].

K_3 Pitch acceleration scaling constant of the C* analysis [seconds^2].

K_θ The 'airframe only' gain

K_p Steady state pilot gain

K_q Steady state gain, elevator to pitch rate transfer function

l Distance from aircraft centre of gravity to the head of the pilot. [m]

L_α $\frac{\rho V_T^2 S C_{L_\alpha}}{2mV_T}$, the dimensional derivative of the aerodynamic lift in the wind axis system w.r.t. angle of attack. In the case of an aircraft with negligible control surface lift this parameter is an approximation of the inverse of τ_{θ_2}. [1/second]

L_{δ_e} $\frac{\rho V_T^2 S C_{L_{\delta_e}}}{2mV_T}$, the dimensional derivative of the aerodynamic lift in the wind axis system w.r.t. elevon deflection [1/second]

m Aircraft mass [kg]

m Mass (inertia) matrix of a multi-degree-of-freedom system

M_α Dimensional derivative of the aerodynamic pitch moment in the wind axis system w.r.t. angle of attack

M_q Dimensional derivative of the aerodynamic pitch moment in the wind axis system w.r.t. pitch rate of the aircraft

M_V Dimensional derivative of the aerodynamic pitch moment in the wind axis system w.r.t. true airspeed

M_{δ_e} Dimensional derivative of the aerodynamic pitch moment in the wind axis system w.r.t. elevator (or elevon) deflection

$M_{\dot{\alpha}}$ Dimensional derivative of the aerodynamic pitch moment in the wind axis system w.r.t. the rate of change of the angle of attack

M_{F_s} $M_{\delta_e}\left(\frac{\delta_e}{F_s}\right)_{SS}$, the derivative of aerodynamic moment around the pitch axis with respect to elevator (or elevon) stick force at steady state conditions.

n Aircraft load factor $\frac{L}{mg}$, or the normal acceleration of aircraft [g's]

n_α Load factor gradient [g/rad]

$\overline{q}$ Dynamic pressure or $\frac{1}{2}\rho V_T^2$ [N/m^2]

q Pitch rate of aircraft [rad/s]

q_g Pitch rate due to gust velocity [rad/s]

q_{rel} Pitch rate of aircraft relative to surrounding air [rad/s]

S Wing area [m^2]

s Laplace operator [1/rad]

s Quarter chord sweep angle [°]

s_r Eigenvalue with index r, of a generic multi degree of freedom system

s_r^* The complex conjugate of s_r

T_{2_p} Time to double, the time for the dynamic mode to double in amplitude [seconds]

V_e	True airspeed at trim condition [m/s] or [km/h]
V_T	True airspeed [m/s]
$\dot{w}_g$	Partial derivative of vertical component of gust velocity with respect to time [m/s^2]
W_g	Maximum value of the vertical gust [m/s]
w_g	Vertical component of gust velocity as function of time [m/s]
$\ddot{\overline{x}}$	Acceleration vector of a multi-degree-of-freedom system
$\dot{\overline{x}}$	Velocity vector of a multi-degree-of-freedom system
$\dot{\mathbf{x}}$	State vector in state space representation
$\overline{X}$	Longitudinal distance rearward from the aircraft CG to the wing aerodynamic centre
$\overline{x}$	Displacement vector of a multi-degree-of-freedom system
X_α	Dimensional derivative of the aerodynamic force in the X-direction of the wind axis system w.r.t. angle of attack
X_V	Dimensional derivative of the aerodynamic force in the X-direction of the wind axis system w.r.t. true airspeed
X_{δ_e}	Dimensional derivative of the aerodynamic force in the X-direction of the wind axis system w.r.t. elevator (or elevon) deflection
x_{cg}	Distance between the leading edge of the wing on the symmetry axis of the aircraft and the CG [m]
$\dot{\overline{y}}$	Acceleration vector of a multi-degree-of-freedom system (State space substitution)
$\overline{y}$	Velocity vector of a multi-degree-of-freedom system (State space substitution)

$\dot{z}$	State space substitution variable
z	Derivative of state space substitution variable
Z_α	Dimensional derivative of the aerodynamic force in the Z-direction of the wind axis system w.r.t. angle of attack
Z_q	Dimensional derivative of the aerodynamic force in the Z-direction of the wind axis system w.r.t. pitch rate of the aircraft
Z_V	Dimensional derivative of the aerodynamic force in the Z-direction of the wind axis system w.r.t. true airspeed
Z_{δ_e}	Dimensional derivative of the aerodynamic force in the Z-direction of the wind axis system w.r.t. elevator (or elevon) deflection
$Z_{\dot{\alpha}}$	Dimensional derivative of the aerodynamic force in the Z-direction of the wind axis system w.r.t. the rate of change of the angle of attack
α	Angle of attack [rad or degrees]
$\dot{\alpha}$	Rate of change of angle of attack [rad/s]
γ	Outboard wing sweep angle (See Figure 4.2). [rad or degrees]
δ_e	Elevator (or elevon) deflection angle [rad]
ζ	Damping ratio []
ζ_p	Phugoid mode damping ratio []
ζ_r	The damping ratio of the r^{th} mode of a generic multi degree of freedom system []
ζ_{sp}	Short period mode damping ratio []
$\ddot{\theta}$	Pitch acceleration of the aircraft. [rad/s^2]
$\dot{\theta}$	Pitch rate [rad/s]
θ	Pitch angle [rad or degrees]

θ_e Error between the commanded pitch attitude and the aircraft pitch attitude [rad]

Λ Angle of sweep of wing quarter-chord line [degrees]

λ Wavelength of the vertical gust disturbance [m]

ρ Density of air [kg/m^3]

τ_{θ_2} Numerator time constant (airframe lead time constant) of pitch rate to elevator deflection transfer function [seconds]

τ_{p_1} Time constant of control system lead element [seconds]

τ_{p_2} Time constant of control system lag element [seconds]

χ Aspect ratio, $\frac{b^2}{S}$ []

ω Circular frequency [rad/s]

ω_d Damped natural frequency [rad/s]

ω_r The natural frequency of the r^{th} mode of a generic multi degree of freedom system [rad/s]

ω_{n_p} Phugoid mode natural frequency [rad/s]

$\omega_{n_{sp}}$ Short period mode natural frequency [rad/s]

$\angle$ Signifies Bode phase angle of a transfer function

$\left(\frac{\theta}{\theta_e}\right)^*$ $\frac{\theta}{\theta_e}$ transfer function with uncompensated pilot. This transfer function is considered as uncompensated when only a gain was used to achieve the Neal-Smith performance standards.

$\left(\frac{\delta_e}{F_s}\right)_{SS}$ Steady state gearing between elevator (or elevon) deflection and elevator stick force [rad/N]

$\frac{\theta}{\theta_c}$ The closed-loop transfer function of the aircraft plus control system plus pilot

$\frac{\theta}{\theta_e}$ The open-loop transfer function of the aircraft plus control system plus pilot

$\frac{\theta}{F_s}$ The open-loop transfer function of the aircraft plus control system

Abbreviations

AR Aspect ratio of wing

BW Bandwidth [rad/s]

BW_{MIN} Minimum bandwidth frequency

BWB Blended Wing Body

CAP Control anticipation parameter

CFD Computational Fluid Dynamics

CG Centre of Gravity

dB Decibel units for Bode amplitude, where amplitude in $dB = 20\log_{10}$ [amplitude]

GPS Global Positioning System

IP Initial point (for a bombing run)

$J - UCAS$ Joint Unmanned Combat Air System

PIO Pilot induced oscillation

PR Pilot rating (of aircraft handling qualities)

UAV Unmanned Air Vehicle

VLM Vortex Lattice Method

Subscripts

e Elevon, as used in δ_e

e Equivalent, as used with V_e

g Gust

r Index number, typically of an eigenvalue, circular natural frequency or damping ratio

rel Relative

SS Steady state