Investigation into the Longitudinal Handling Characteristics of a Gull Wing Planform Tailless Aircraft

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Introduction

- The gull wing configuration
  - Planform inspired by nature
  - Novel flight control system
    - variable outboard wing sweep for trim control
    - twisting elevons for pitch and roll control
    - rudders for directional control and circulation distribution control

- Advantages of swept tailless gull wing configuration
  - Novel trim control eliminates problem of limited elevon range
  - Less parasitic drag because it is tailless
  - Optimisation with respect to induced drag (best Oswald efficiency)
• The tailless swept gull wing configuration

- FWD swept inboard
- Wing sweep: 20° to 36°
- Sweep hinge
- Elevon
- Flaps
- Winglet with rudder
- Pilot/cockpit
- Inboard dihedral
- Outboard anhedral
Handling Qualities

- Why are good handling qualities important?
  - Lowers pilot workload.
  - Modern gliders all have good handling qualities.

- The relevance of handling qualities to tailless aircraft
  - Need to investigate whether a tailless aircraft can have both
    - good handling qualities &
    - high performance
  - Because modern gliders have both
Handling Qualities

- Pitch dynamics investigated in isolation
  - Pitch dynamics can be isolated mathematically
  - Many tailless aircraft handling quality issues related to pitch dynamics.
  - Usually studied in isolation.

- Assumptions
  - Lateral dynamics handling qualities are acceptable.
  - No tip stall.
Flying Wing Technology

- WeltenSegler (1921)
Flying Wing Technology

- Horten
- GAL/56
- Fauvel
- Fledermaus/Wampir
Flying Wing Technology

- Horten aircraft
Flying Wing Technology

- GAL/56
Flying Wing Technology

- Fauvel AV36 (flying plank)
Flying Wing Technology

- Nietoperz and Wampir
Flying Wing Technology

- Northrop aircraft
Flying Wing Technology

- Marske design - The pioneer (flying plank)
Flying Wing Technology

- Long break before the new flying wing aircraft:
  - Laminar flow wing profiles were developed
  - Performance increase of conventional sailplanes
  - Improved handling qualities of conventional designs.
  - Development cost of tailless aircraft very high (approx. 10 times)

- Then in late 1970’s and early 1980’s:
  - Laminar flow low $C_M$ wing profiles developed by Horstmann and Quast
  - High performance tailless aircraft now possible
Flying Wing Technology

- Modern flying wing sailplanes
  - SB-13
  - Pyxis
  - Flair 30
  - SWIFT/ Millennium
  - Exulans
Flying Wing Technology

- Akaflieg Braunschweig SB-13 Arcus
Flying Wing Technology

- SWIFT
Flying Wing Technology

- Flair 30
Flying Wing Technology

- Military aircraft
  - B2 stealth bomber with digital controllers
  - X36 - Reconfigurable flight controls
  - X-45
  - ScanEagle

- Civil aircraft
  - Blended Wing Body (BWB) designs
Flying Wing Technology

- Northrop B2 bomber
Flying Wing Technology

- X-planes
  - X-43

- X-45
Flying Wing Technology

- Blended Wing Body concepts
Flying Wing Technology

- Boeing ScanEagle UAV
Flight Model

- Coefficient build-up method
  - 3DOF aircraft equations of motion
  - Aircraft stability derivatives

- Technical challenges
  - No prototype aircraft - no flight test data
  - Dynamic scaling very difficult
  - Sweep angles is additional variable
Flight model

- Solution
  - Hand calculation methods estimate stability derivatives
  - VLM methods
  - General investigation - impacts accuracy of model
  - Linear aerodynamics, Small disturbance theory

- Gull wing aircraft modelled was the Exulans glider:
Flight model

- Four different CG configurations were chosen for evaluation
  - Specified at 30° sweep angle (fixed reference)
  - Chosen so that a wide variety of static margins were evaluated
  - Static margin range of models
    - -2.3% to 18%
Flight Model

- Examples of lift and moment curves versus sweep angle.

\[ C_L \] vs. \( \alpha \)

\[ C_M \] vs. \( \alpha \)

Non-linear stall not modeled
Flight model

- Low pitch damping and pitch inertia
- Pitch damping could be as high as -40 /rad (conventional), but now:

Absolute magnitude increases with sweep angle - damping surface further from CG with sweep
Flight model

- Inertia could $43 \times 10^6 \, \text{kg.m}^2$ for C5 Galaxy, $1690 \, \text{kg.m}^2$ for Piper Cherokee, but for the Exulans case:

  - Increases with sweep angle - mass moves away from CG with sweep

  - Varies parabolically with sweep

![Graph showing the variation of pitch inertia with cutboard wing sweep angle]
Flight model

- Elevon control authority

Higher control authority with larger sweep angles - elevons move away from CG with sweep
Performance aspects

- O-point, C-point, E-point

![Graph showing position of O-point, C-point, and E-point relative to neutral point and outboard wing sweep angle.]

- O-point aft of NP
- C-point and NP almost co-incident
- E-point forward of NP
Sensitivity Analysis

- Uncertainty regarding the exact magnitude of certain mathematical model parameters, because
  - Prototype not built
  - No wind tunnel model (dynamic similarity)

- Need to quantify the effect of uncertainty on handling qualities

- The following parameters were investigated
  - Control authority ($\pm 20\%$)
  - Static margin (-5 to 15% @ 30° sweep)
  - Damping ($\pm 50\%$)
  - Pitch inertia ($\pm 10\%$)
Sensitivity Analysis

- The following parameters had the most effect on response:
  - Control authority
  - Static margin
  - Damping

- The following had a small effect for the range investigated:
  - Inertia
Handling Quality Evaluation Methods

- Time domain simulation
  - Step responses
  - Gust responses
- C-star

- Eigenvalue analysis (poles) & Military Flying Qualities Analysis
- Zero analysis
- Neal-Smith analysis

- Mönnich-Dalldorff criteria
- Tumbling analysis
- Step response example

![Graph showing time domain simulation with rough indication of 17 s and qualitative evaluation of damping.](image)
- Gust response example

- Short period behaviour
  - (Strongly damped)

- Phugoid behaviour

- Cosine gust response function

- Qualitative evaluation
C-star analysis

- Use simulation/flight test step response
- Mixture between normal, pitch acceleration and angular speed around the YY-axis of the aircraft.

\[ C^* = K_1 n + K_2 \dot{\theta} + K_3 \ddot{\theta} \]

- Plotted on the C-star envelope, developed with flight tests
- C-star envelope is defined with normalised \( C^*/F_p \) values

Pilot stick force
C-star analysis

- C-star criterion

![Diagram showing C-star analysis for powered approach and up and away boundaries for fighter aircraft and manoeuvre](image-url)
C-star analysis

- Typical result

![Diagram showing normalised C/F vs time](image-url)
C-star analysis

- Conclusions
  - Exulans has initial response that is unfavourable, but thereafter satisfactory.
  - None of the cases exhibit lightly damped oscillations. Fall inside the C-star boundaries following initial response.
Based on calculation of
- Natural frequency ($\omega_n$) and damping ratio ($\zeta$)
- Short period and phugoid modes

Short period characteristics are most important with respect to handling characteristics (as opposed to phugoid).

Eigenvalue analysis
- Aircraft mathematical model
- Numerical Eigenvalue analysis routine

ASSUMPTION: Pitch to elevator transfer function is related to handling characteristics
Eigenvalue analysis

- For many tailless aircraft, the short period frequency is the same as human response
- 1-2 Hz.

- This has the potential to lead to Pilot Induced Oscillation (PIO)
Eigenvalue analysis

- Pole criteria or “thumbprint” graph

```
Too rapid an initial response – over sensitive
– tendency to PIO

Poor

Acceptable

Response too sluggish

Satisfactory

Too rapid an initial response – over sensitive
– tendency to PIO

Excessive overshoot
– difficult to manoeuvre

Poor

Unacceptable

Excessive compensation required – difficult to trim

Short period damping ratio \( \xi_p \)

Undamped short period natural frequency \( \omega_{sp} \)
```
Eigenvalue analysis

- Typical results for Exulans

- Short period frequency and damping typically: 0.8 to 1.7 Hz
  Damping = 0.5 to 1 (sub-critically damped)

Phugoid mode is lightly damped
Indicates a tendency to PIO
Military flying quality specifications

- MIL-8785 (US DOD handling quality standard)
  - Based on eigenvalue analysis
  - Also takes into account aircraft normal acceleration

- Method:
  - Calculate CAP
  - Plot CAP versus $\zeta_{sp}$
Military flying quality specifications

- MIL-8785 chart

Levels are defined by MIL-8785 standard

Level 1 is best handling qualities
Military flying quality specifications

- Typical results for Exulans

Config 27 - low static margin comes closest to Level 1 flying qualities
Eigenvalue analysis conclusions

- Gull wing planform not satisfactory when only inherent dynamics investigated

BUT

- the zero’s of the pitch to elevator transfer function not investigated with eigenvalue analysis - incomplete picture
Zeros flying quality analysis

- Based on pitch to elevator transfer function of an aircraft.
- Focus on the zeros of this transfer function, not the poles
- Performance criteria based on flight test data
- Gull wing configuration will be placed on these maps.
Zeros flying quality analysis

- Based on the following transfer function:

\[
\frac{\dot{\theta}}{\delta_e} = \frac{K_\dot{\theta} \left( \tau_{\dot{\theta}_2} s + 1 \right)}{s^2 + \frac{2\zeta_{sp}}{\omega_{nsp}} s + 1} + \frac{2\zeta_{sp}}{\omega_{nsp}} s + 1
\]
Zeros flying quality analysis

- $N_{z\alpha} \leq 15$
- $N_{z\alpha} > 15$

$N_{za}$ varies with airspeed
Zeros flying quality analysis

- Typical result

- Not all configurations are favourable though
Zeros flying quality analysis

- **Conclusions**
  - 20% variation in aerodynamic damping does not have a significant effect on handling qualities

- Handling qualities that vary with air speed were investigated:
  - Speeds higher than design trim speeds show poorer handling qualities for the case of the Exulans
Neal-Smith criterion

- Also based on pitch to elevator transfer function

- Takes pilot into account (Models pilot with a servo actuator transfer function)

- Based on a performance chart created from flight test data
Neal-Smith criterion

- Neal Smith mapping
Neal-Smith criterion

- Transfer function of aircraft

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

- Transfer function of pilot (based on TF of actuator)

\[
\frac{F_s}{\theta_e} = K_p e^{-0.3s} \frac{\tau_{p_1} s + 1}{\tau_{p_2} s + 1}
\]
### Neal-Smith criterion

- **Explanation of method**
  - Pilot compensation modeled with lead and lag
Neal-Smith criterion

- Performance criteria

-3dB Droop criteria

3.5 rad/s Bandwidth criteria
Nichols chart explained

- Lead compensation
- Lag compensation
- Gain compensation

Open-loop gain [dB]
Open-loop phase [deg]
3.5 rad/s
-180
-90
-3dB
Hump of curve on the droop performance standard boundary
Neal-Smith criterion

- Results

![Graph showing Neal-Smith criterion results](image-url)
Conclusions

- Gull wing configuration has good handling qualities for a large range of static margins and outboard wing sweep

- A 20% variation in control authority does not have a large effect on handling qualities

- A 20% variation in aerodynamic damping does not have a large effect on handling qualities
Turbulence handling criteria

- Some tailless aircraft have poor handling qualities in turbulent atmosphere

- Mönnich-Dalldorff criteria:

\[
\frac{C_{M\alpha}}{C_{Mq}} < \left( C_{L\alpha} + C_{D_e} \right) \frac{\rho Sc}{2m}
\]

- If TRUE, the aircraft should have good handling qualities in gusty conditions
Turbulence handling criteria

• Results
  • Low static margin configurations have satisfactory gust condition handling qualities
  • Handling qualities deteriorate with altitude
Tumbling criteria

- Definition: Tumbling
- Hangliders prone to this phenomenon

- More analysis and experiments must be done for gull wing configuration to determine exact tumbling characteristics

Gull wing planform in this region: Likely to tumble.
Summary of results

- Region of best Oswald efficiency
Region of most favourable handling qualities
Summary of results

- Superimpose region of good handling quality with region of best Oswald efficiency
Summary of results

- Intersection of region of good handling qualities and best Oswald efficiency
Conclusions

- Gull wing configuration has acceptable handling characteristics for large range of static margins

- A range of CG exist for the gull wing configuration where the aircraft will have both good handling characteristics and good Oswald efficiency

- The gull wing configuration aircraft has good turbulent atmosphere handling characteristics
Questions