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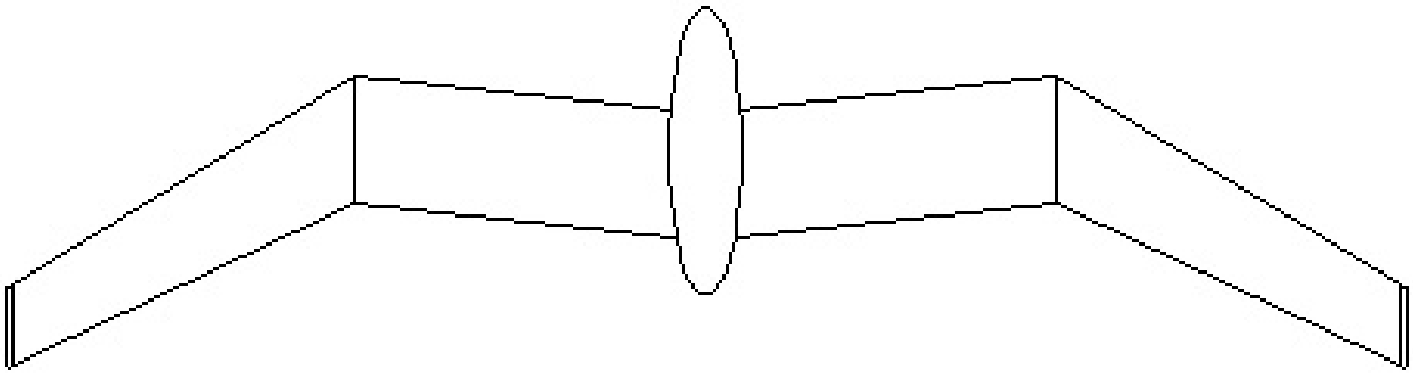
Investigation into the Longitudinal Handling Characteristics of a Gull Wing Planform Tailless Aircraft



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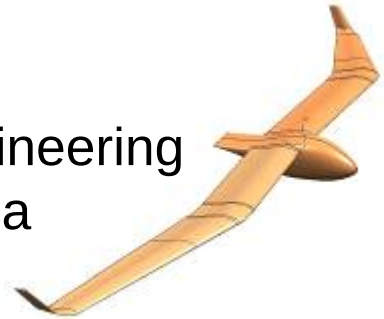
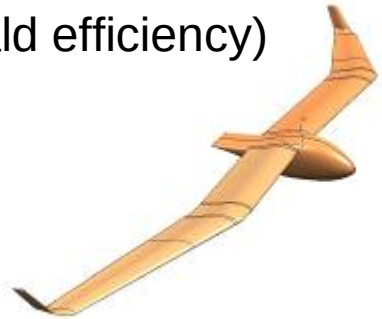


July 2008

Introduction

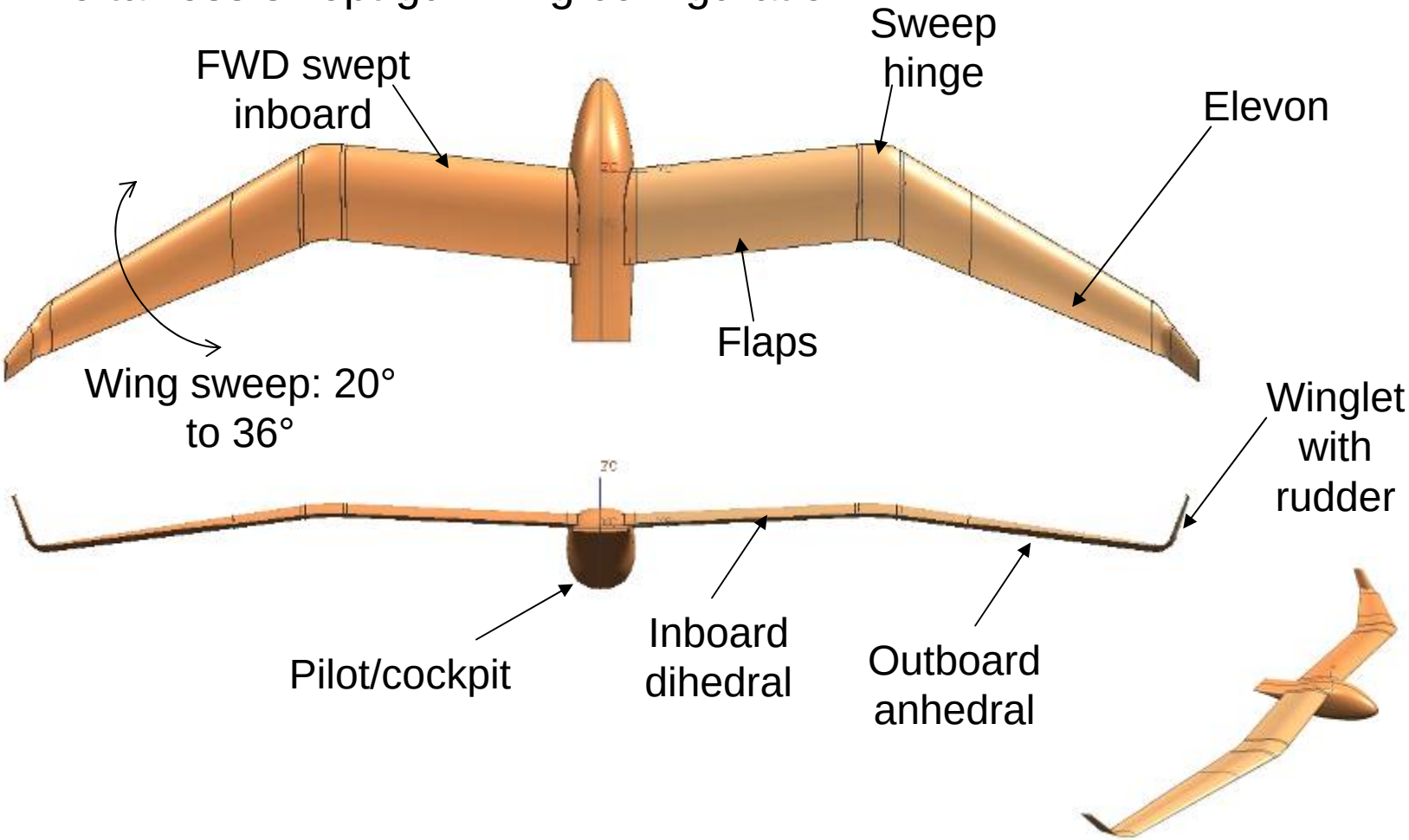
- The gull wing configuration
  - Planform inspired by nature
  - Novel flight control system
    - variable outboard wing sweep for trim control
    - twisting elevons for pitch and roll control
    - rudders for directional control and circulation distribution control

- 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)



Introduction

- The tailless swept gull wing configuration



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

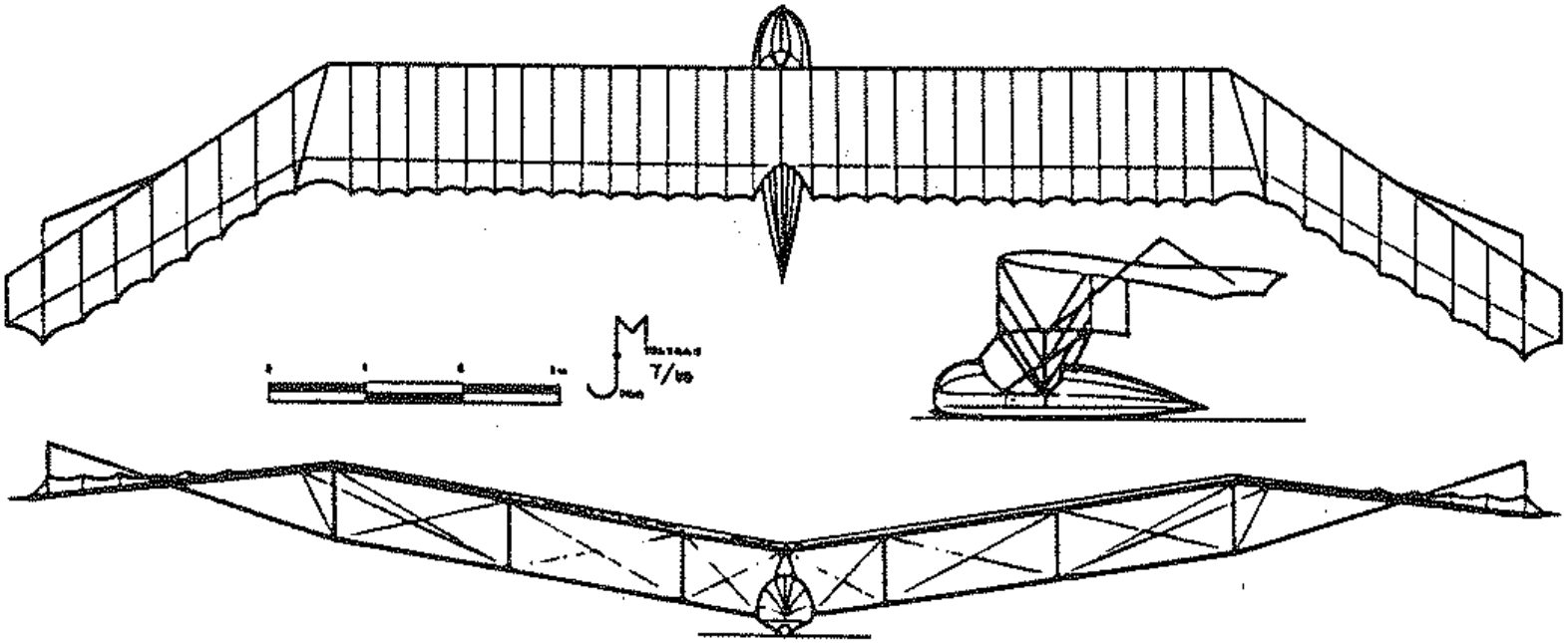
Handling Qualities

- 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)

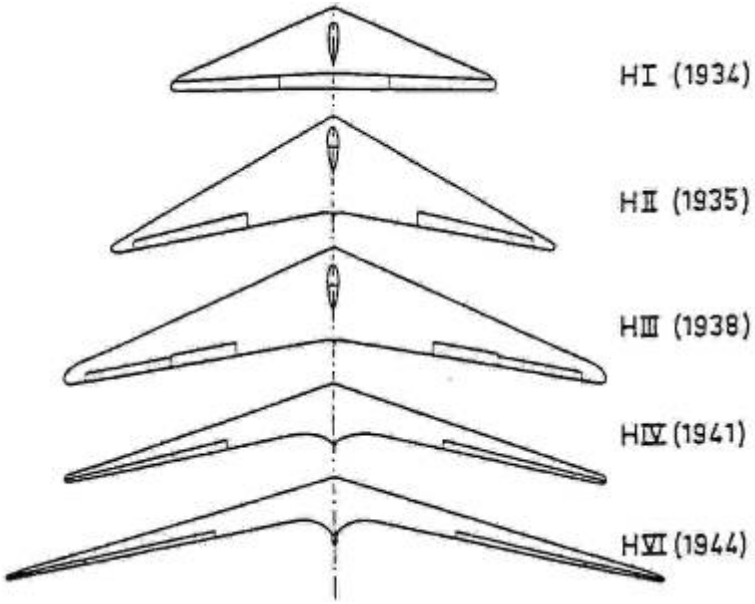


Flying Wing Technology

- Horten
- GAL/56
- Fauvel
- Fledermaus/Wampir

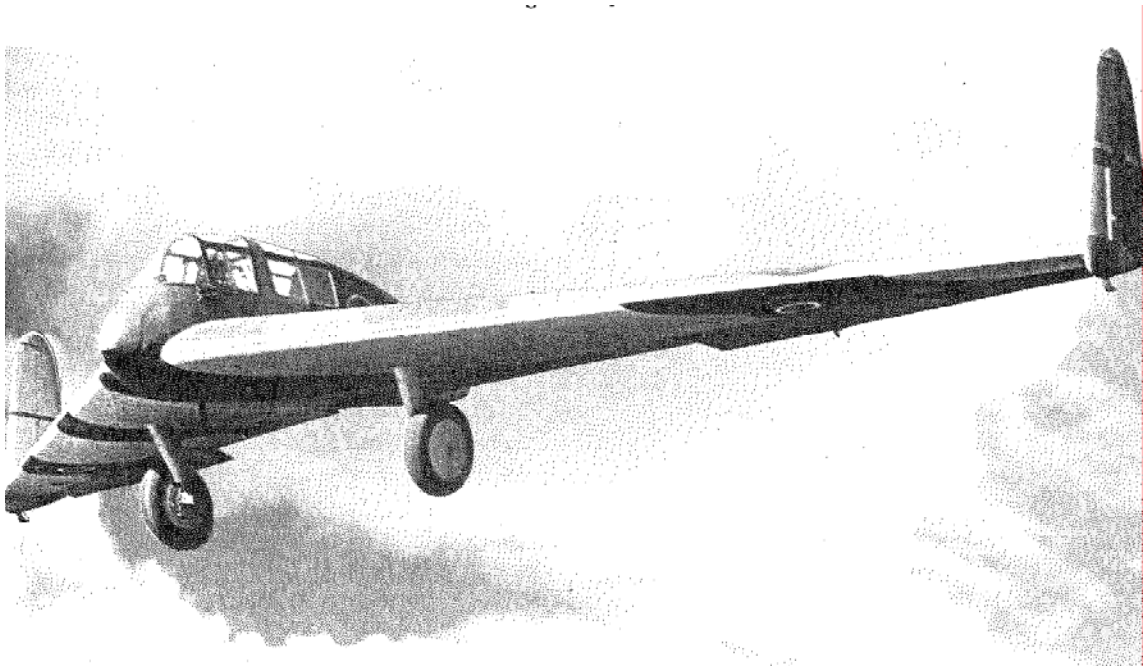
Flying Wing Technology

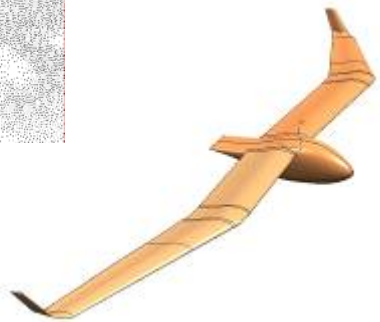
- Horten aircraft



Flying Wing Technology

- GAL/56



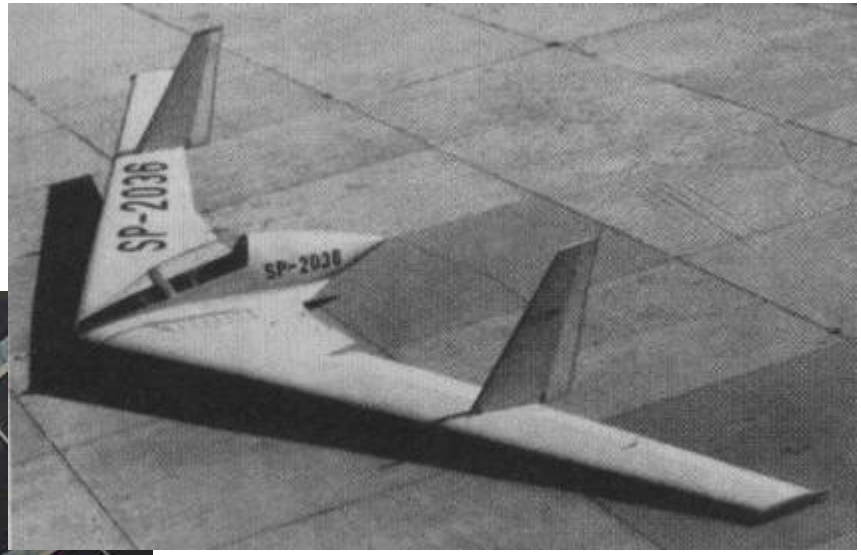


Flying Wing Technology

- Fauvel AV36 (flying plank)

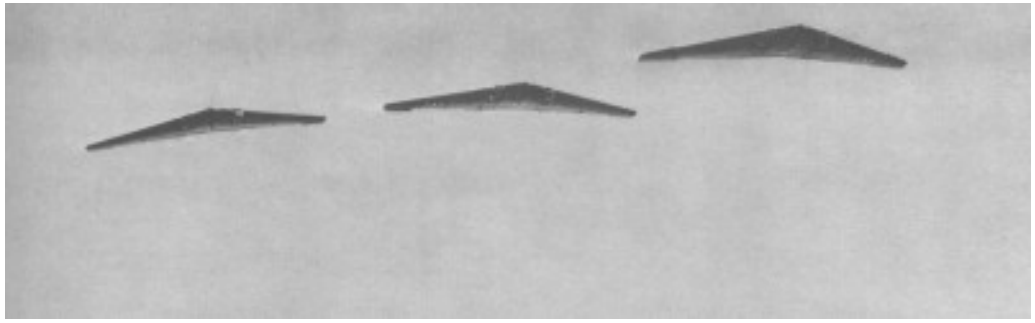
Flying Wing Technology

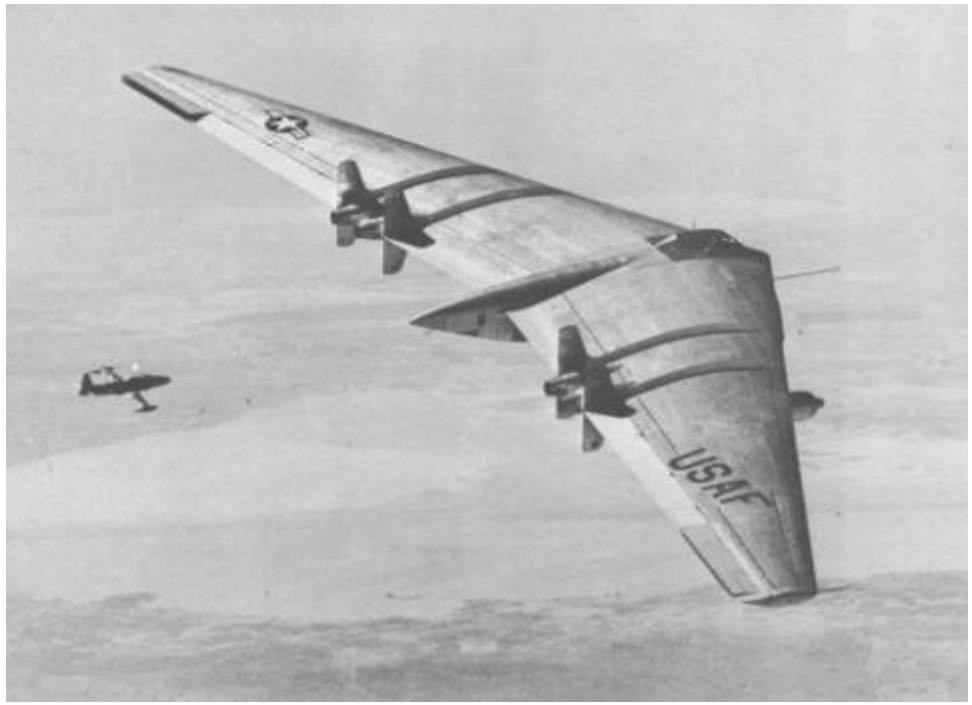
- Nietoperz and Wampir



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

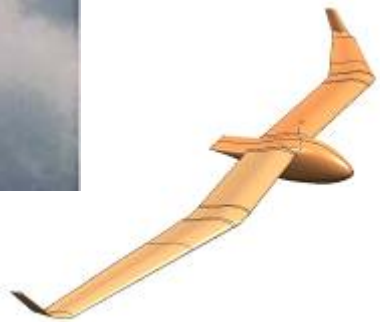
- Modern flying wing sailplanes
  - SB-13
  - Pyxis
  - Flair 30
  - SWIFT/ Millennium
  - Exulans

Flying Wing Technology

- Akaflieg Braunschweig SB-13 Arcus

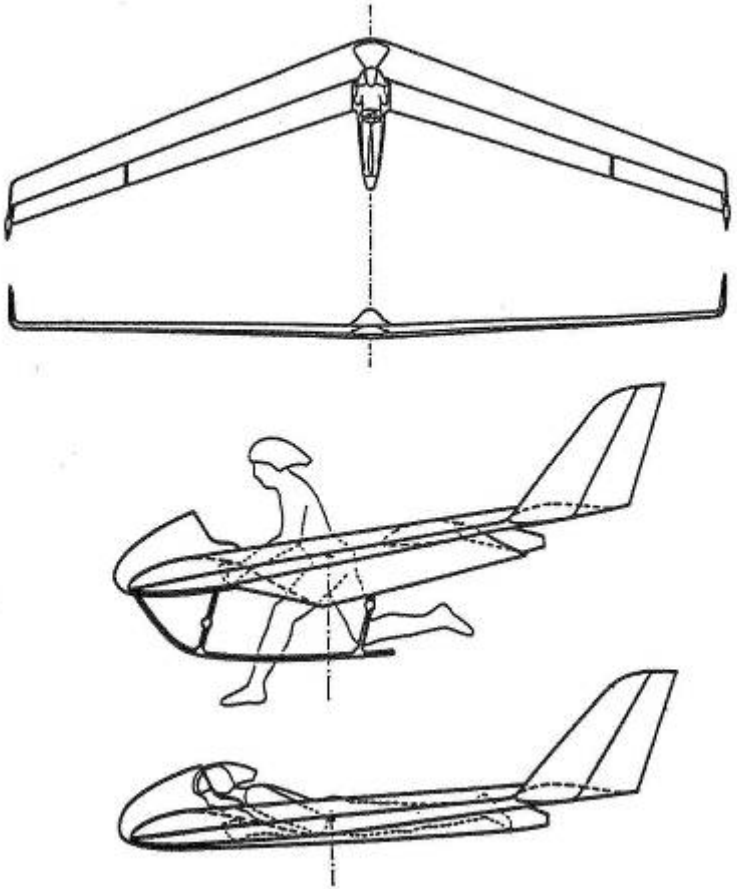
Flying Wing Technology

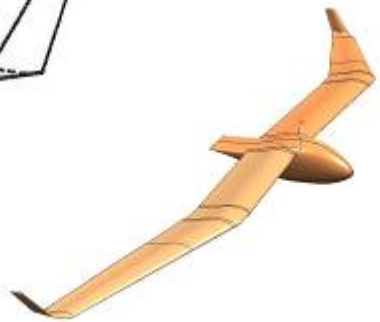
- SWIFT



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

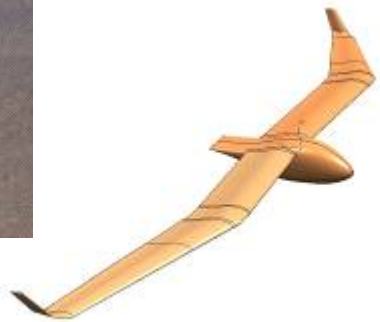
Flying Wing Technology

- Northrop B2 bomber

Flying Wing Technology

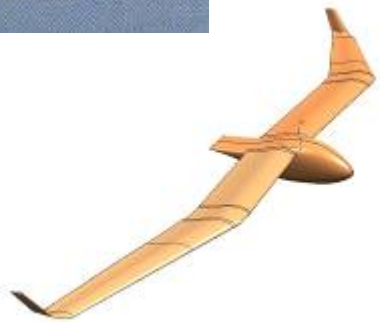
- X-planes
  - X-43

  - X-45



Flying Wing Technology

- Blended Wing Body concepts



Flying Wing Technology

- Boeing ScanEagle UAV

Flight Model

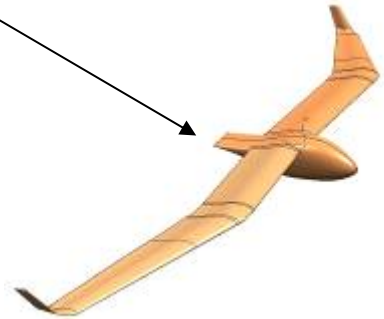
- Coefficient build-up method
  - 3DOF aircraft equations of motion
  - Aircraft stability derivatives

- 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:

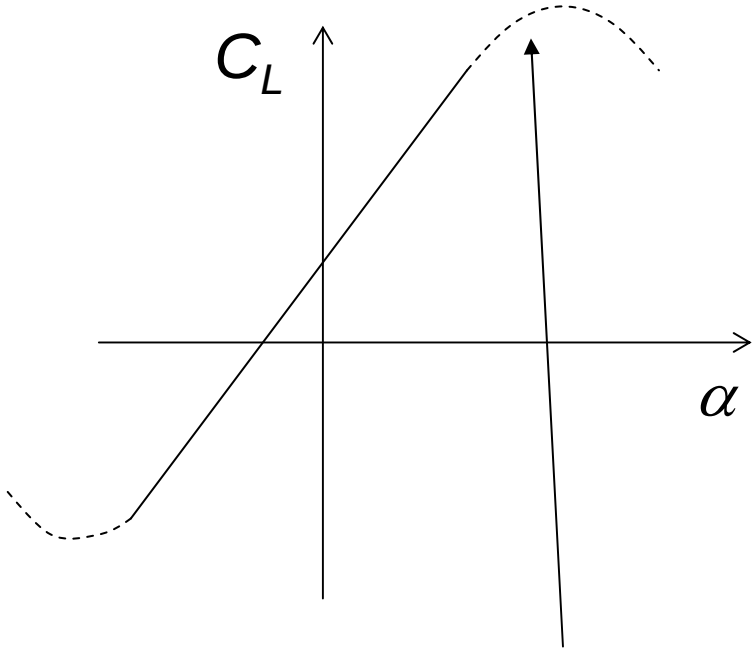


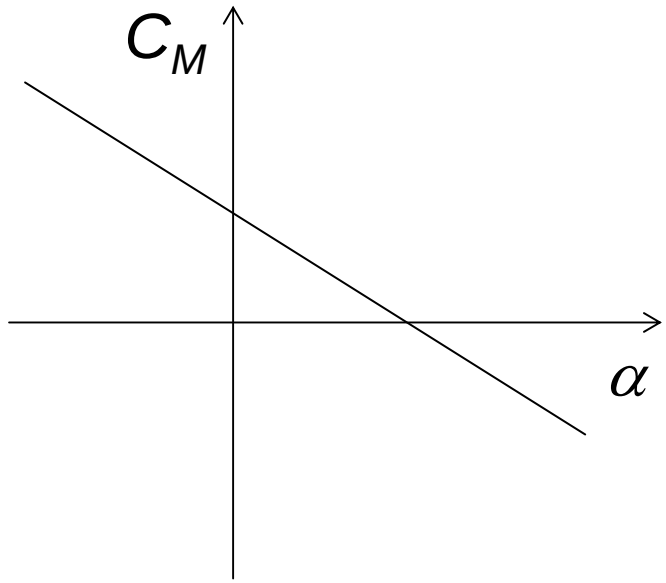
Flight model

- 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.

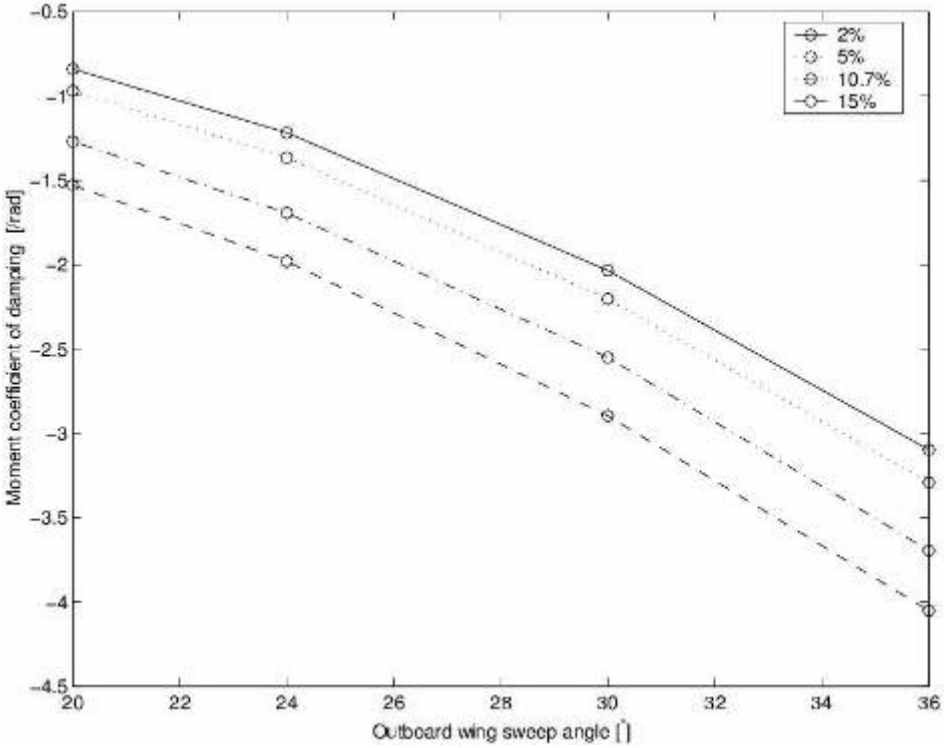




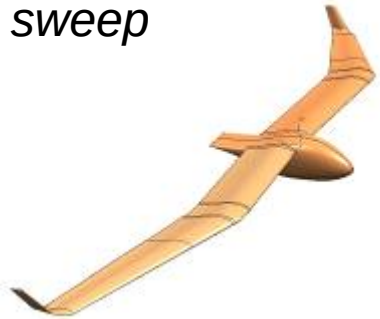
Non-linear stall not modeled

Flight model

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

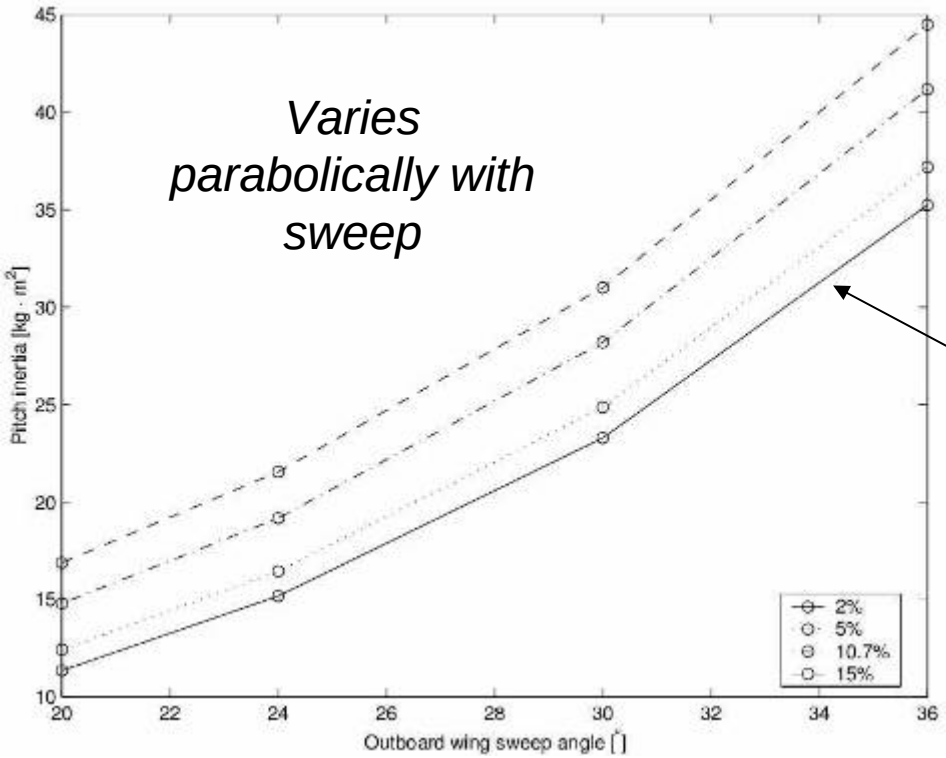


Absolute magnitude increases with sweep angle - damping surface further from CG with sweep

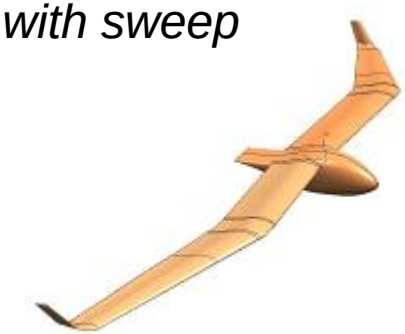


Flight model

- Inertia could 43×10^6 kg.m^2 for C5 Galaxy, 1690 kg.m^2 for Piper Cherokee, but for the Exulans case:

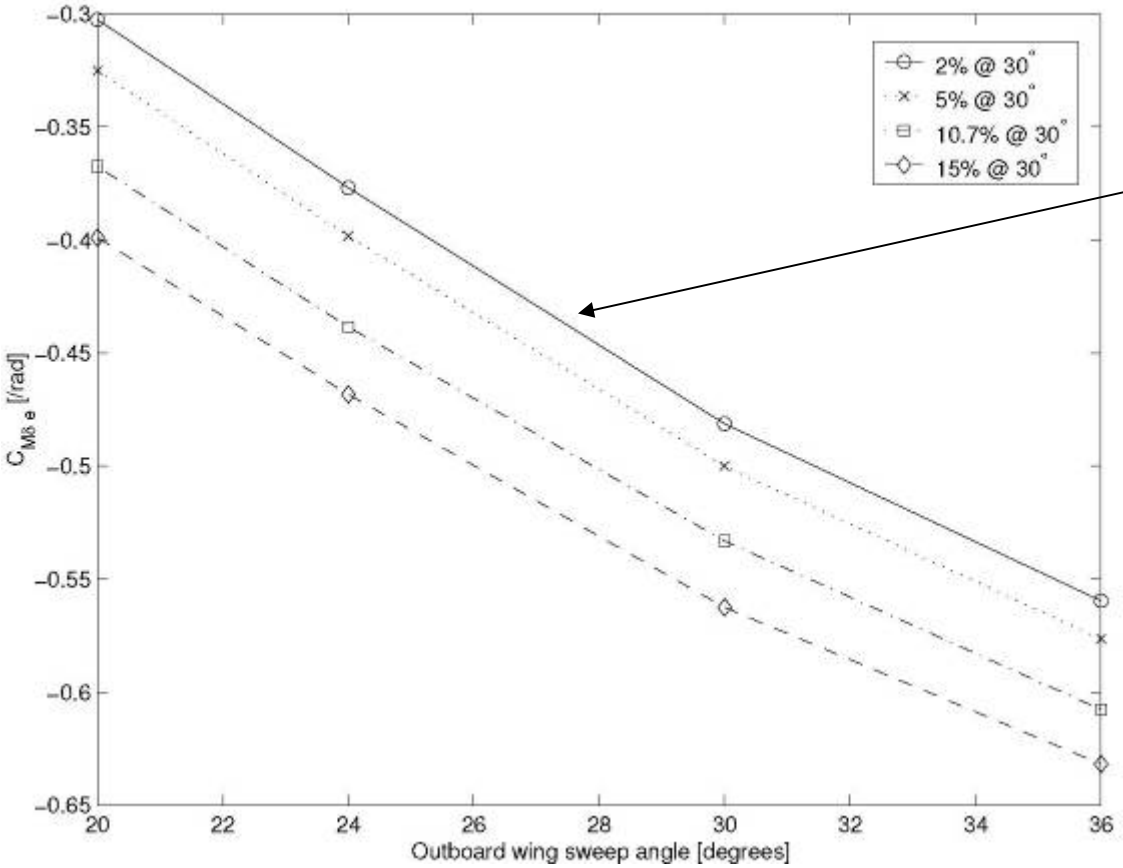


Increases with sweep angle - mass moves away from CG with sweep



Flight model

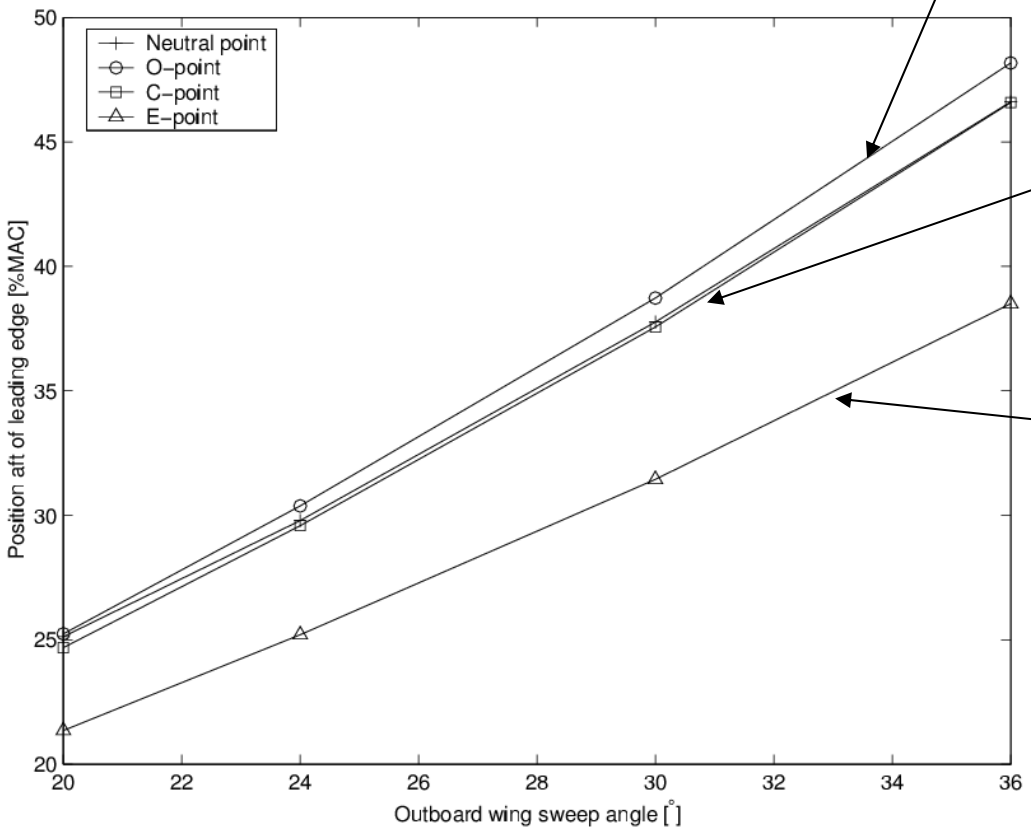
- Elevon control authority



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

Performance aspects

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



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 (±20%)
  - Static margin (-5 to 15% @ 30° sweep)
  - Damping (±50%)
  - Pitch inertia (±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

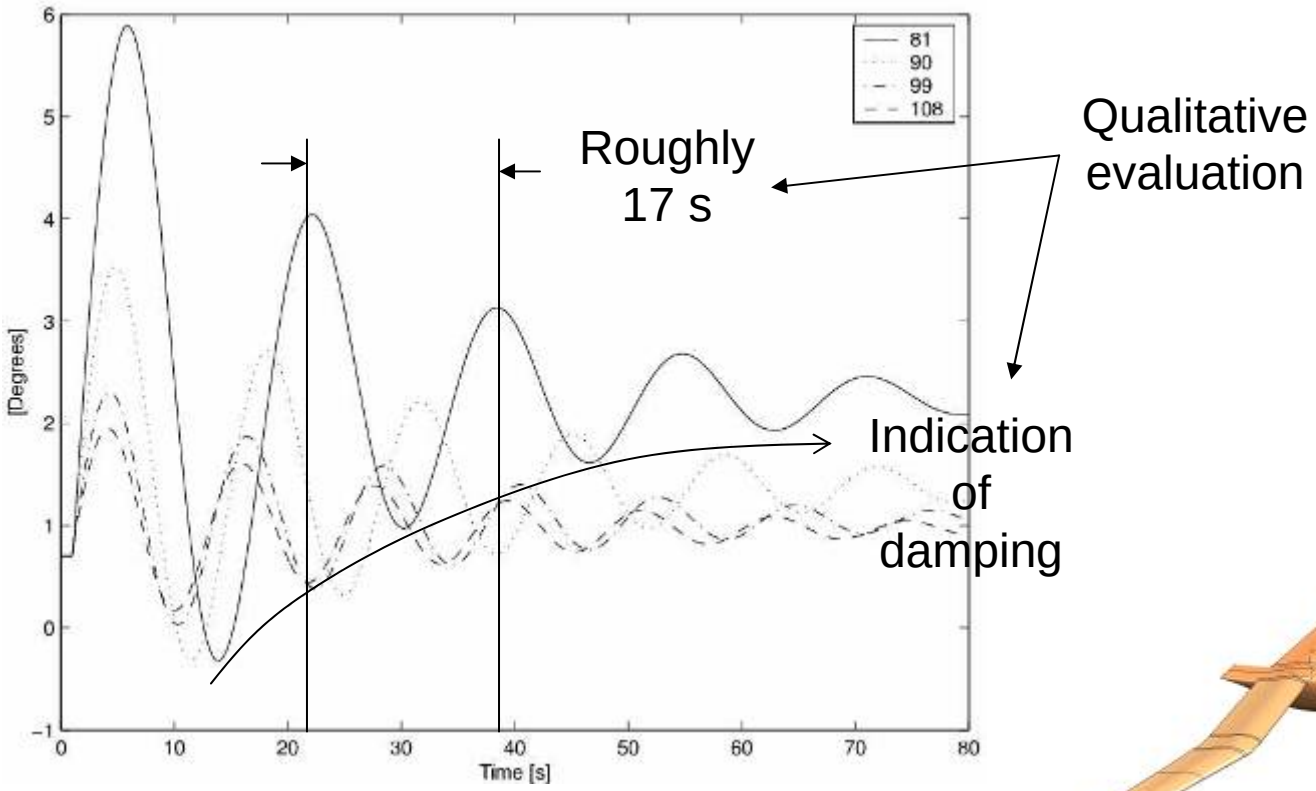
- Time domain simulation
  - Step responses
  - Gust responses
- C-star

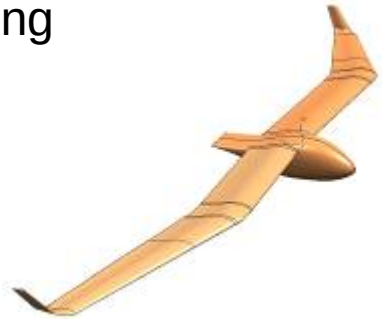
- Eigenvalue analysis (poles) & Military Flying Qualities Analysis
- Zero analysis
- Neal-Smith analysis

- Mönnich-Dalldorff criteria
- Tumbling analysis

Time Domain Simulation

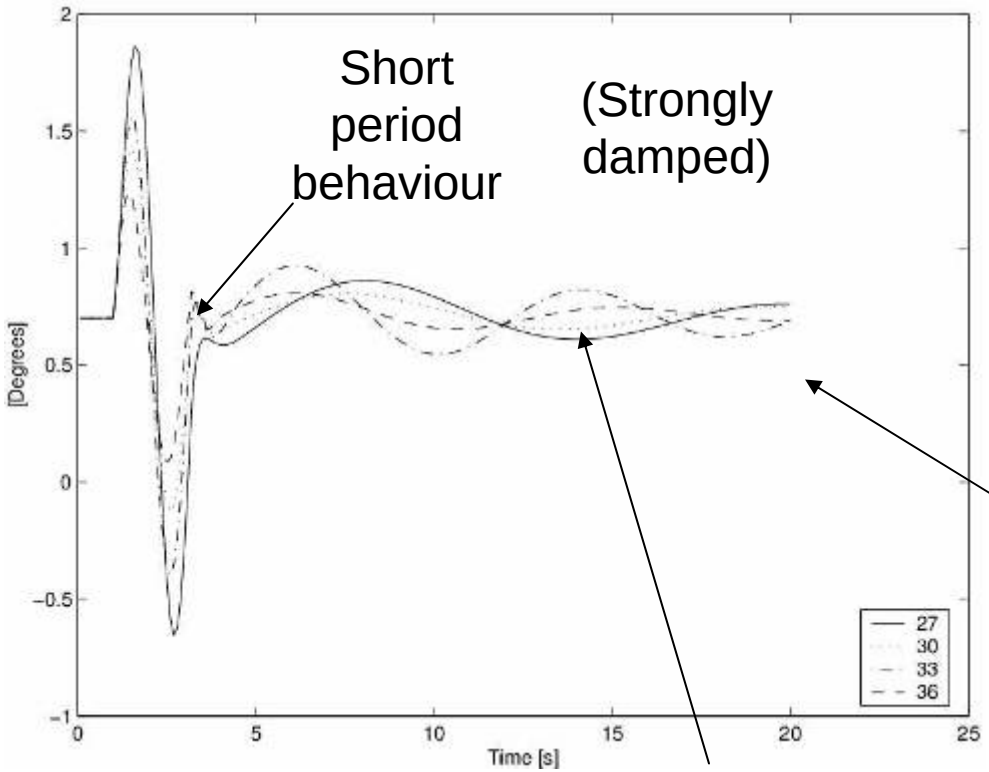
- Step response example

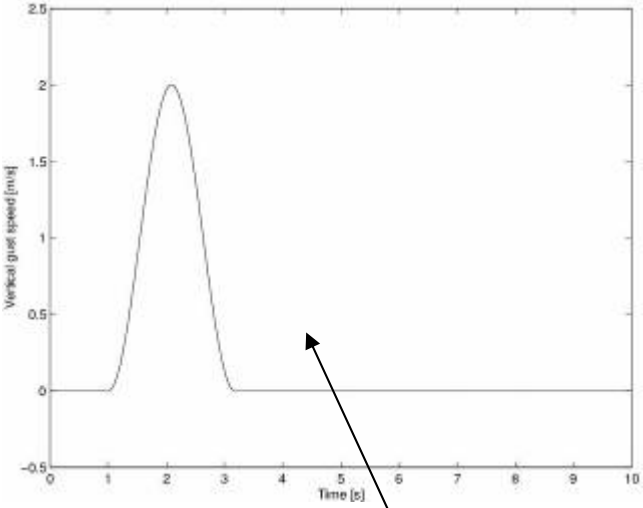




Time Domain Simulation

- Gust response example





Cosine gust response function

Qualitative evaluation

Phugoid behaviour

C-star analysis

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

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

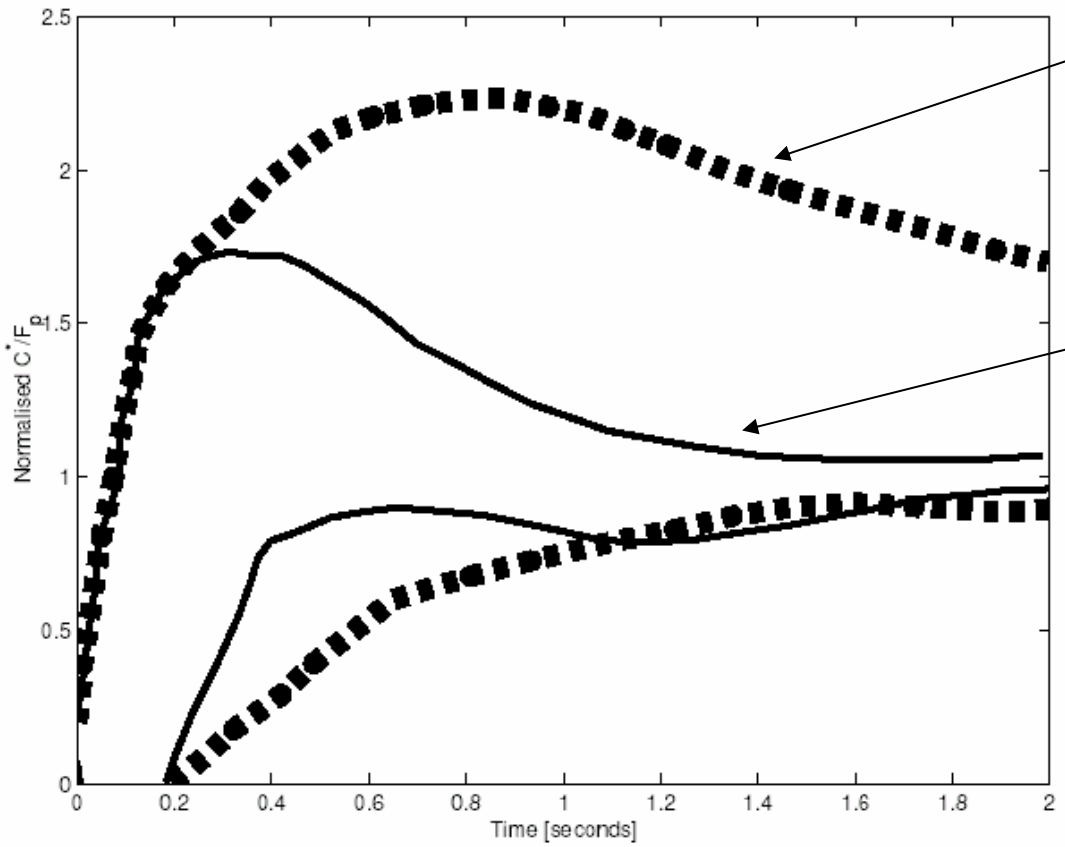
- Plotted on the C-star envelope, developed with flight tests

- C-star envelope is defined with normalised C^*/F_p values

Pilot stick force

C-star analysis

- C-star criterion

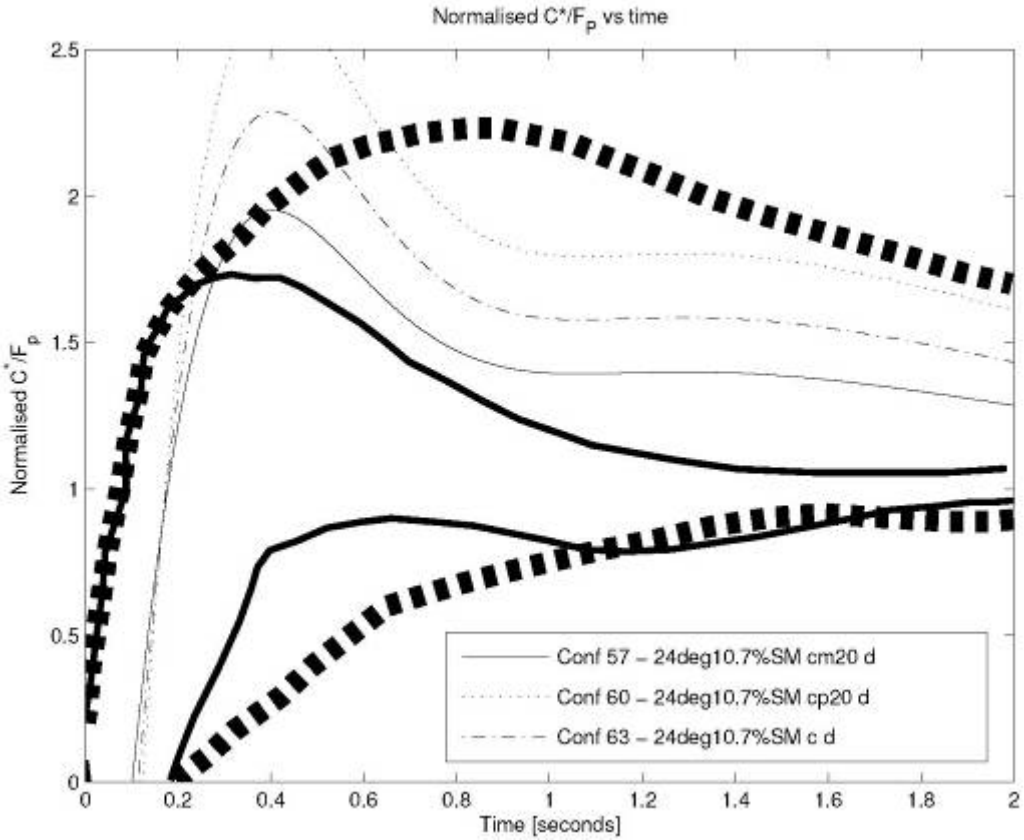


Powered approach - landings

Up and away boundaries - fighter aircraft and manoeuvre

C-star analysis

- Typical result



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.

Eigenvalue analysis

- Based on calculation of
  - Natural frequency (ω_n) and damping ratio (ζ)

  of
  - short period and phugoid modes

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

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

- Eigenvalue analysis
  - Aircraft mathematical model
  - Numerical Eigenvalue analysis routine

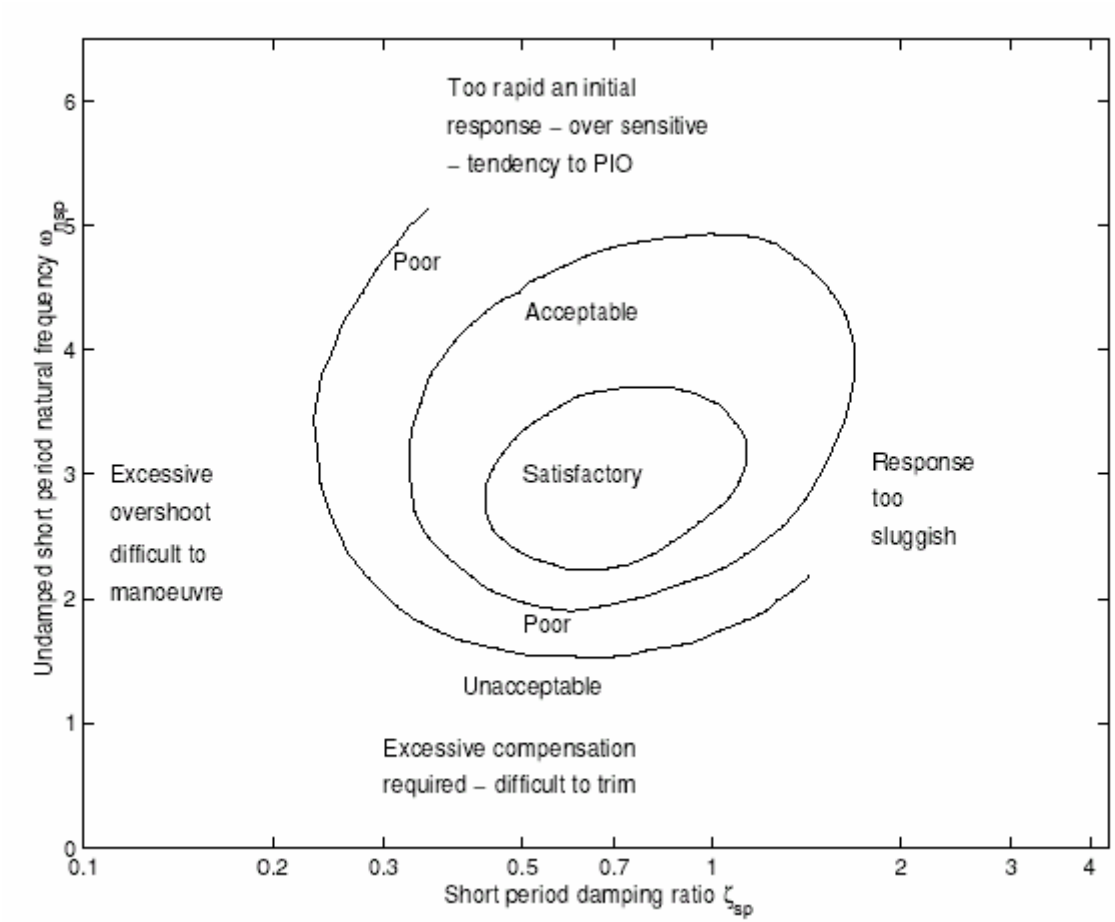
Eigenvalue analysis

- 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)

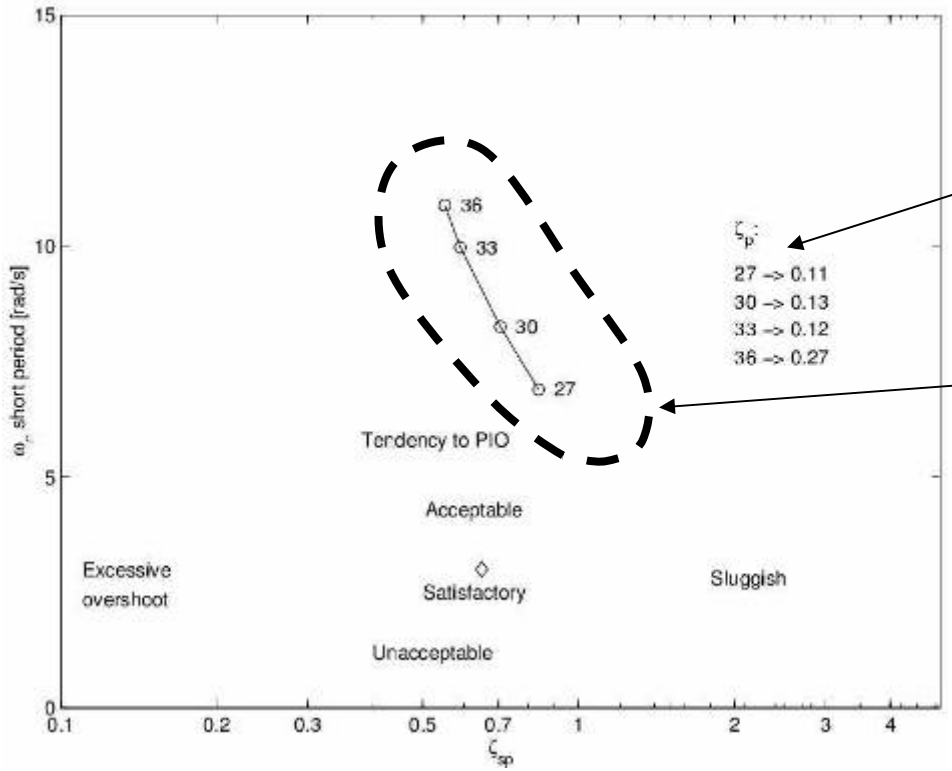
Eigenvalue analysis

- Pole criteria or “thumbprint” graph



Eigenvalue analysis

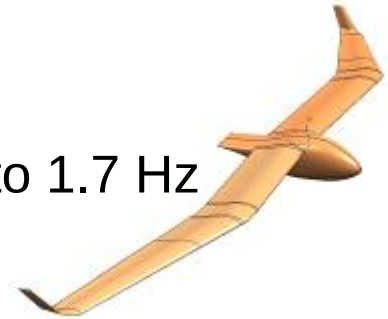
- Typical results for Exulans



Phugoid mode is lightly damped

Indicates a tendency to PIO

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



Military flying quality specifications

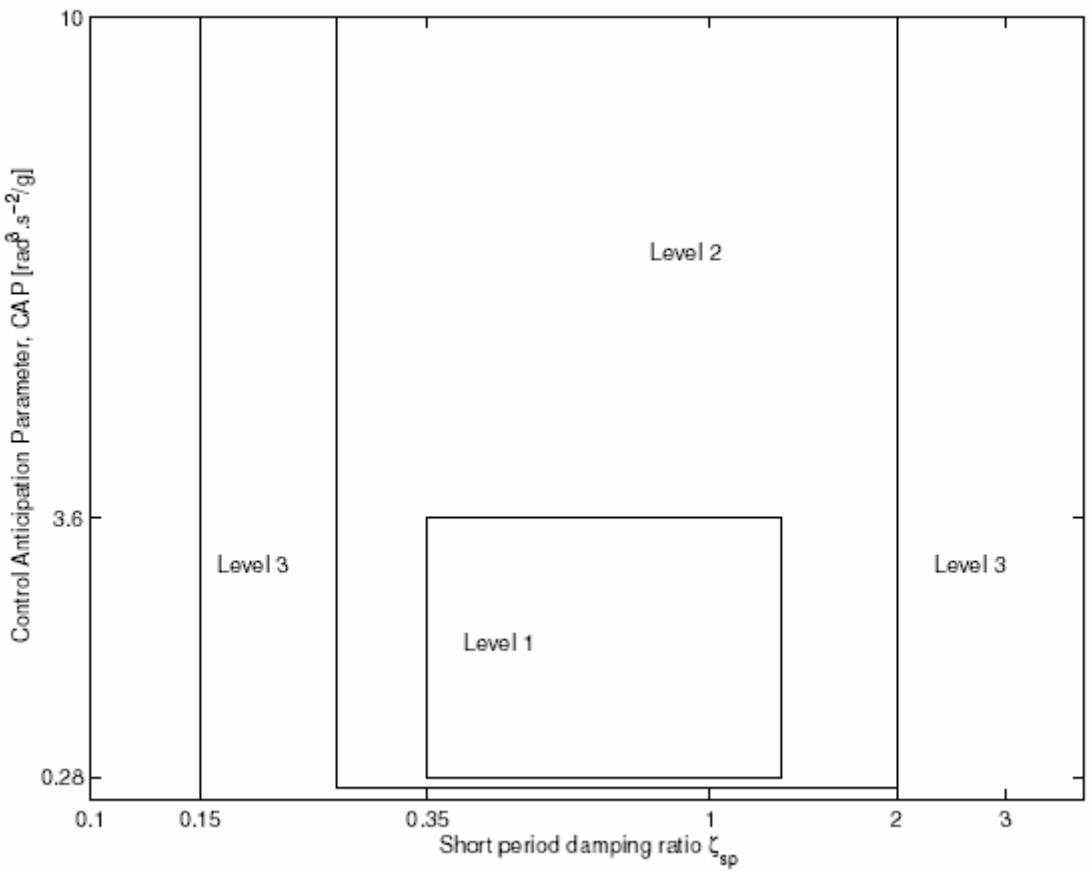
- MIL-8785 (US DOD handling quality standard)

- Based on eigenvalue analysis
- Also takes into account aircraft normal acceleration

- Method:
  - Calculate CAP
  - Plot CAP versus ζ_{sp}

Military flying quality specifications

- MIL-8785 chart

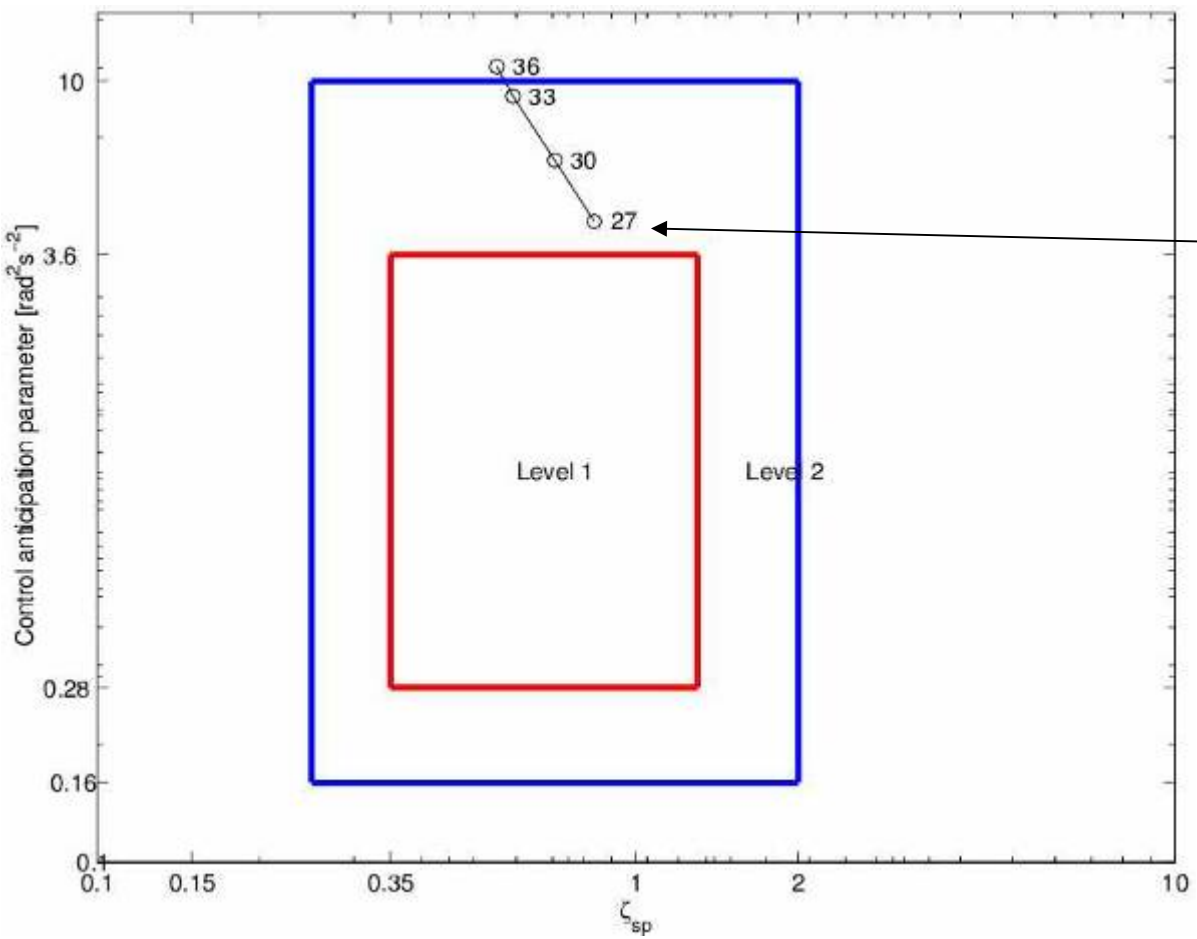


Levels are defined by MIL- 8785 standard

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.

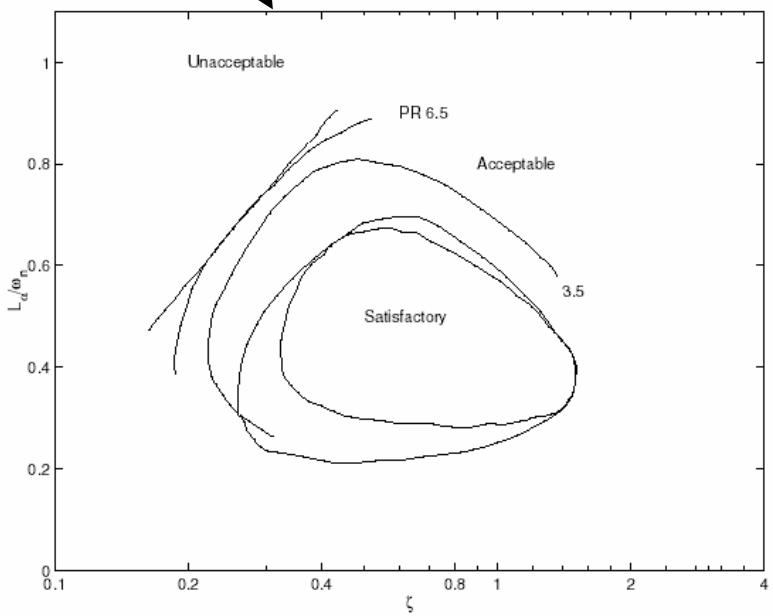
Zeros flying quality analysis

- Based on the following transfer function:

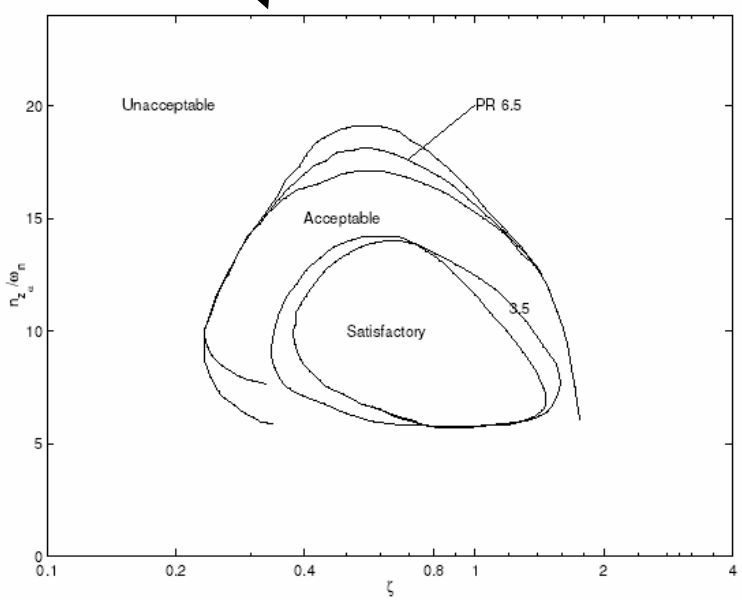
$$\frac{\dot{\theta}}{\delta_e} = \frac{K_{\dot{\theta}}\left(\tau_{\theta_2} s + 1\right)}{\frac{s^2}{\omega_{n_{sp}}^{\ 2}} + \frac{2\zeta_{sp}}{\omega_{n_{sp}}} s + 1}$$

Zeros flying quality analysis

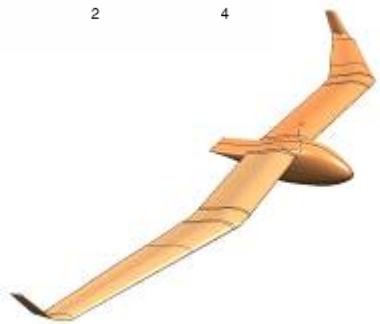
- $N_{z\alpha}$ <= 15



$N_{z\alpha}$ > 15

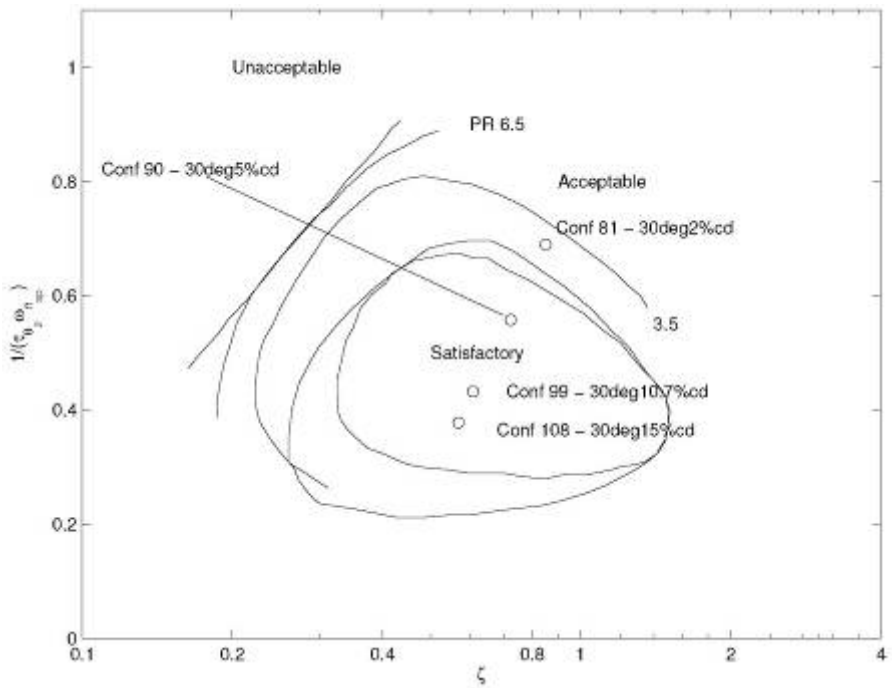


N_{za} varies
with airspeed



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

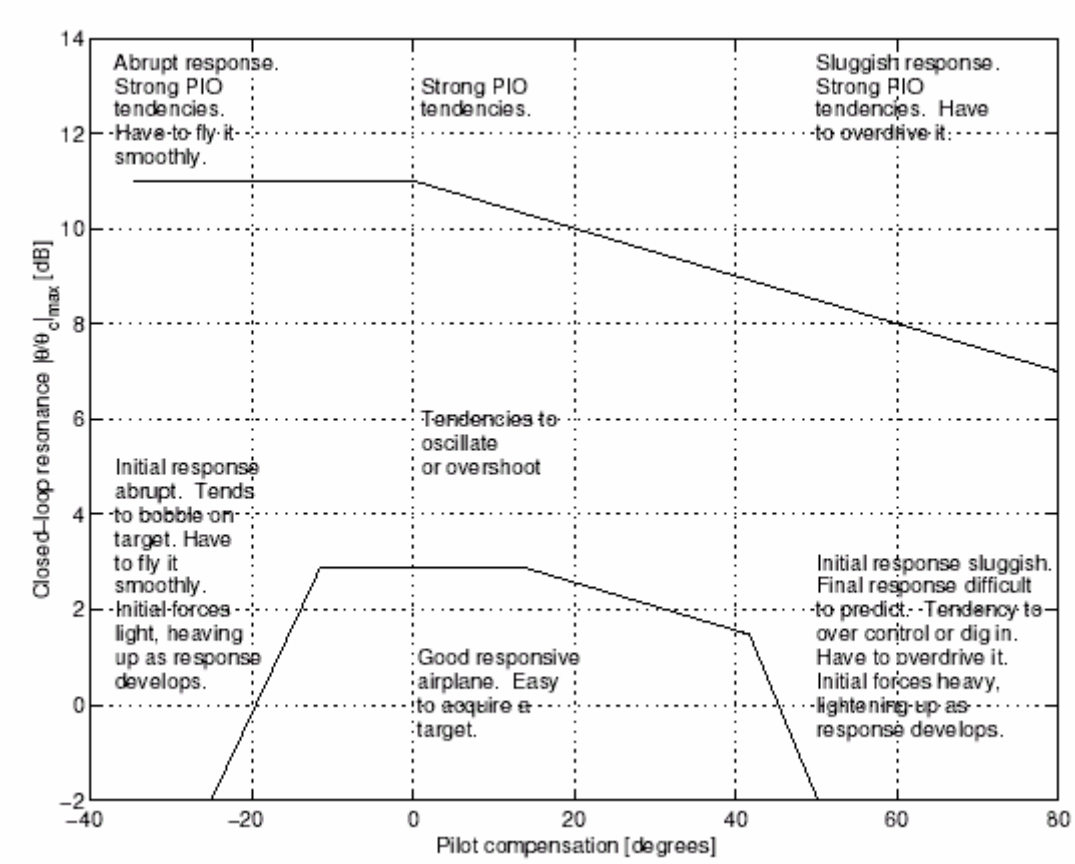
- Also based on pitch to elevator transfer function

- 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

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

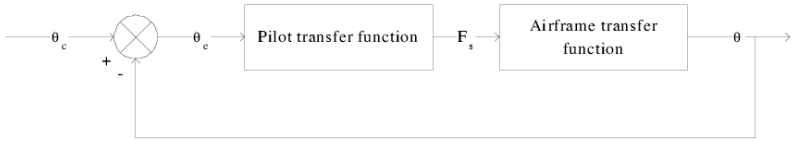
$$\frac{\theta}{F_s} = \frac{K_\theta\left(\tau_{\theta_2} s + 1\right)}{s\left(\frac{s^2}{\omega_{n_{sp}}{}^2} + \frac{2\zeta_{sp}}{\omega_{n_{sp}}} s + 1\right)}$$

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

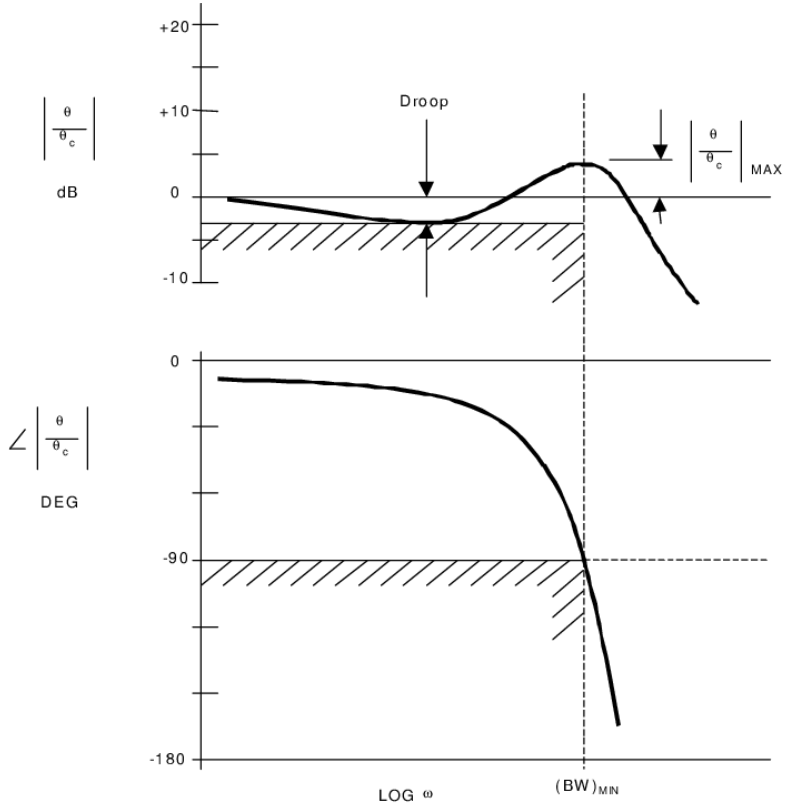
$$\frac{F_s}{\theta_e} = K_p e^{-0.3s} \frac{\tau_{p_1} s + 1}{\tau_{p_2} s + 1}$$

Neal-Smith criterion

- Explanation of method

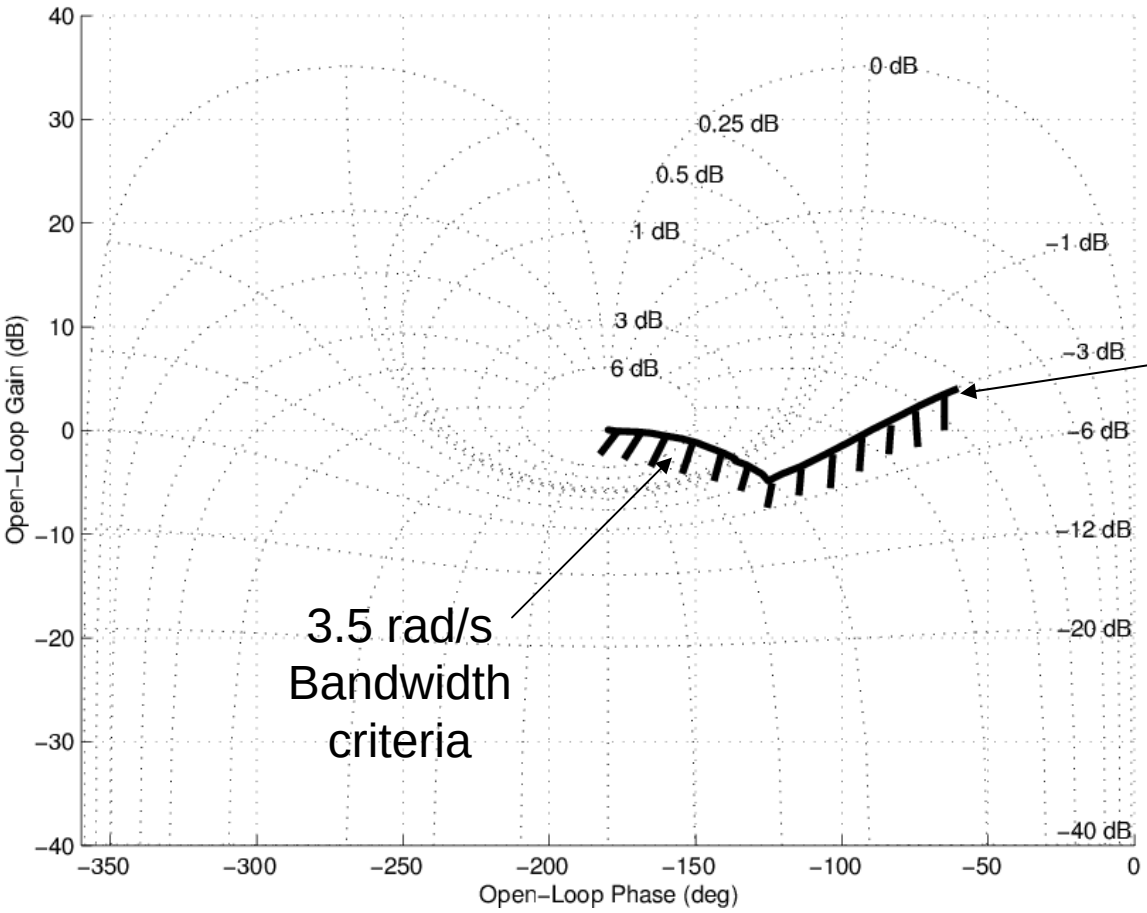


  - Pilot compensation modeled with lead and lag



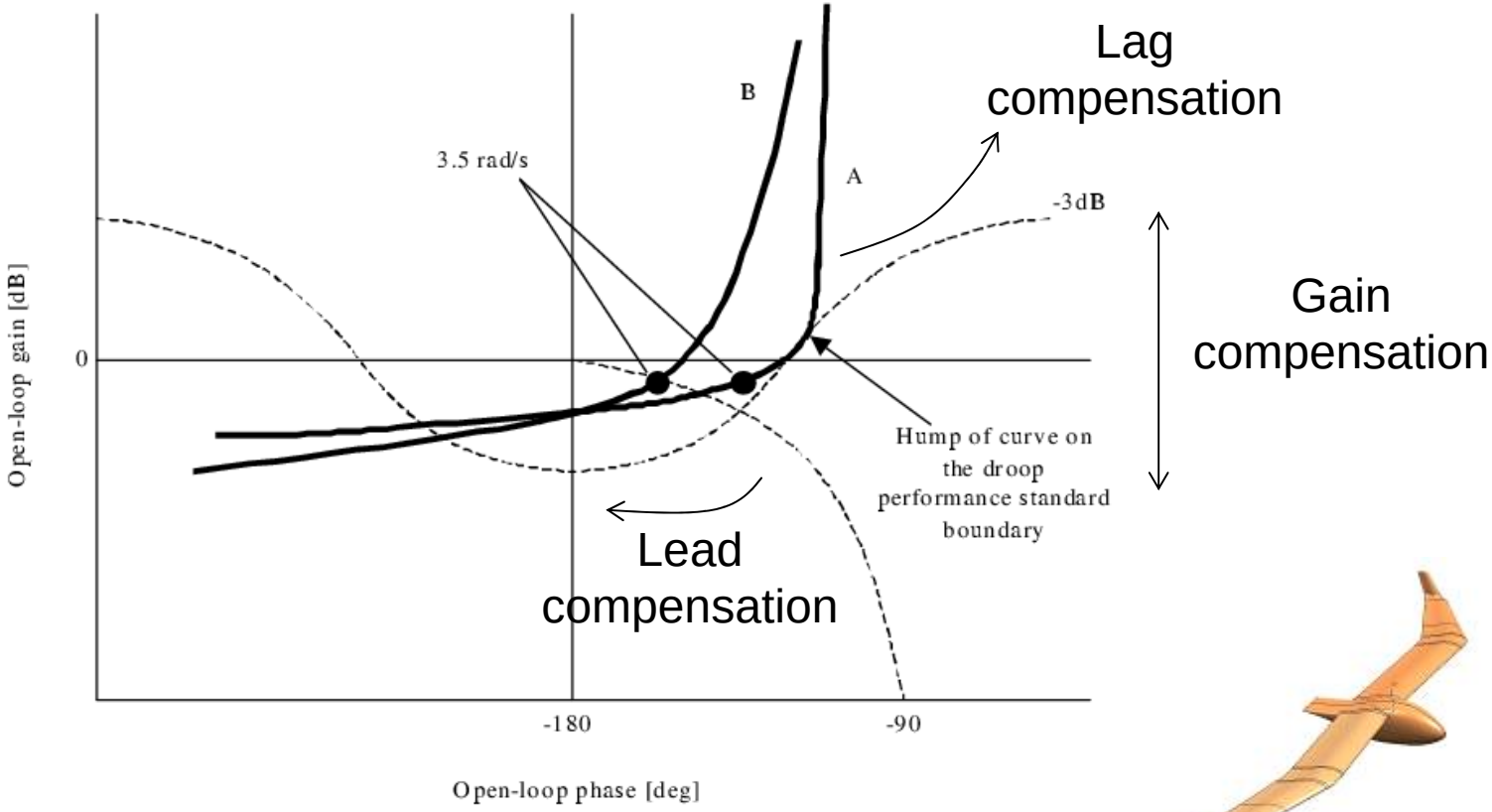
Neal-Smith criterion

- Performance criteria



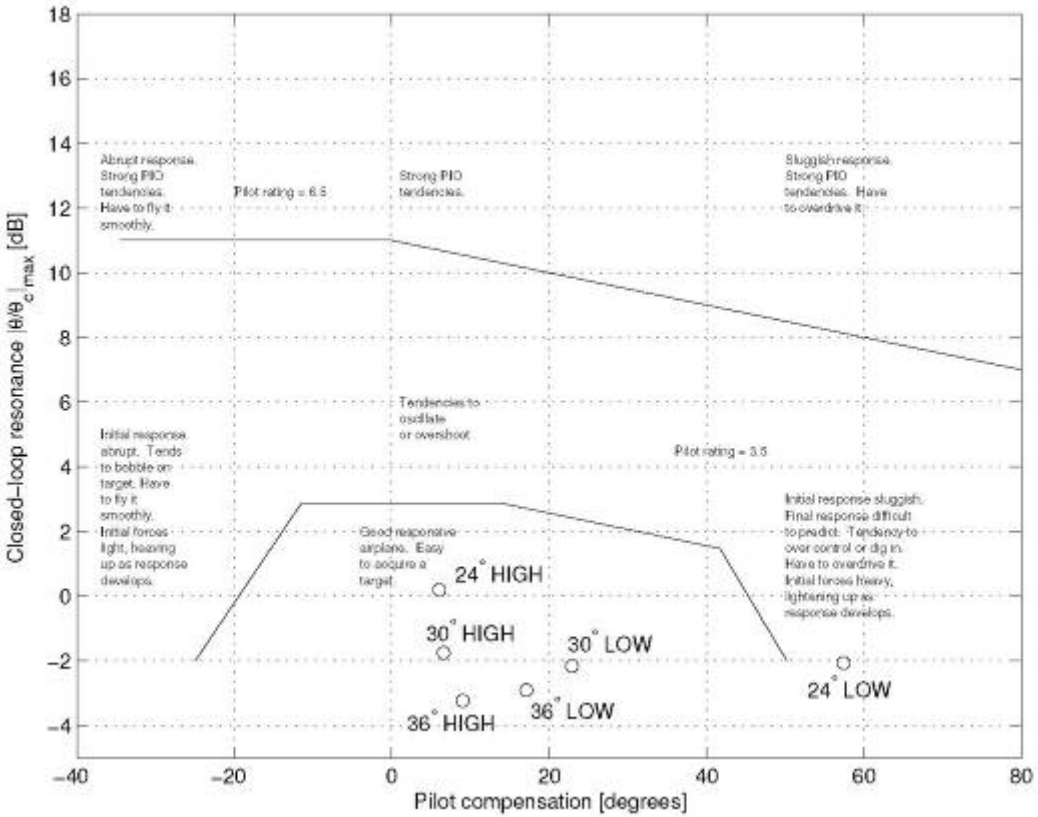
Neal-Smith criterion

- Nichols chart explained



Neal-Smith criterion

- Results



Neal-Smith criterion

- 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:

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

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

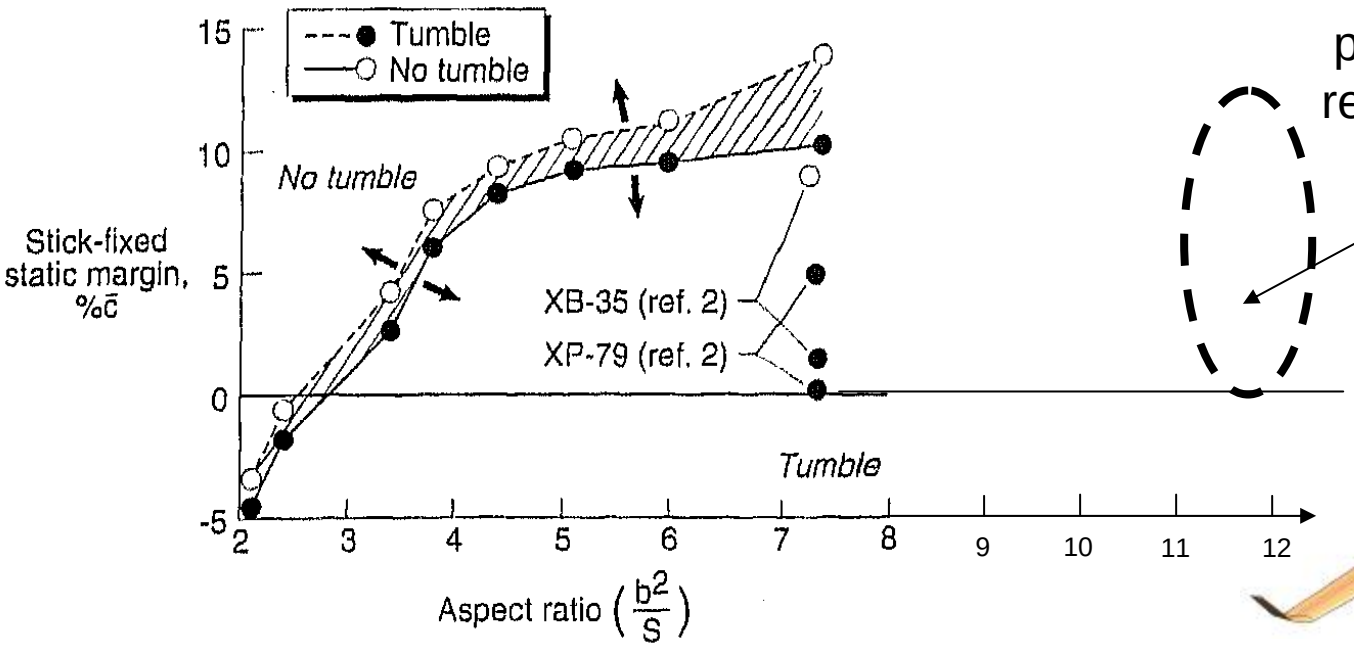
Turbulence handling criteria

- Results
  - Low static margin configurations have satisfactory gust condition handling qualities
  - Handling qualities deteriorate with altitude

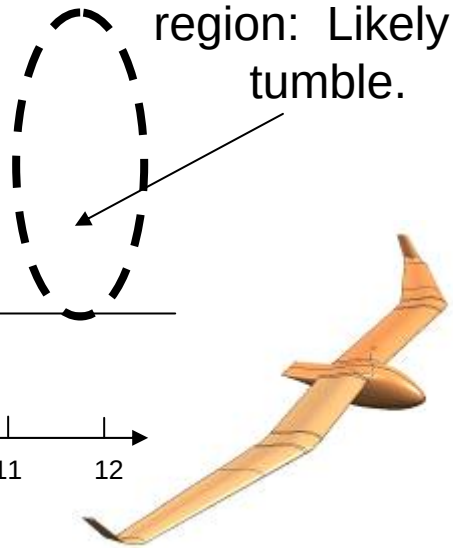
Tumbling criteria

- Definition: Tumbling
- Hangliders prone to this phenomenon

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

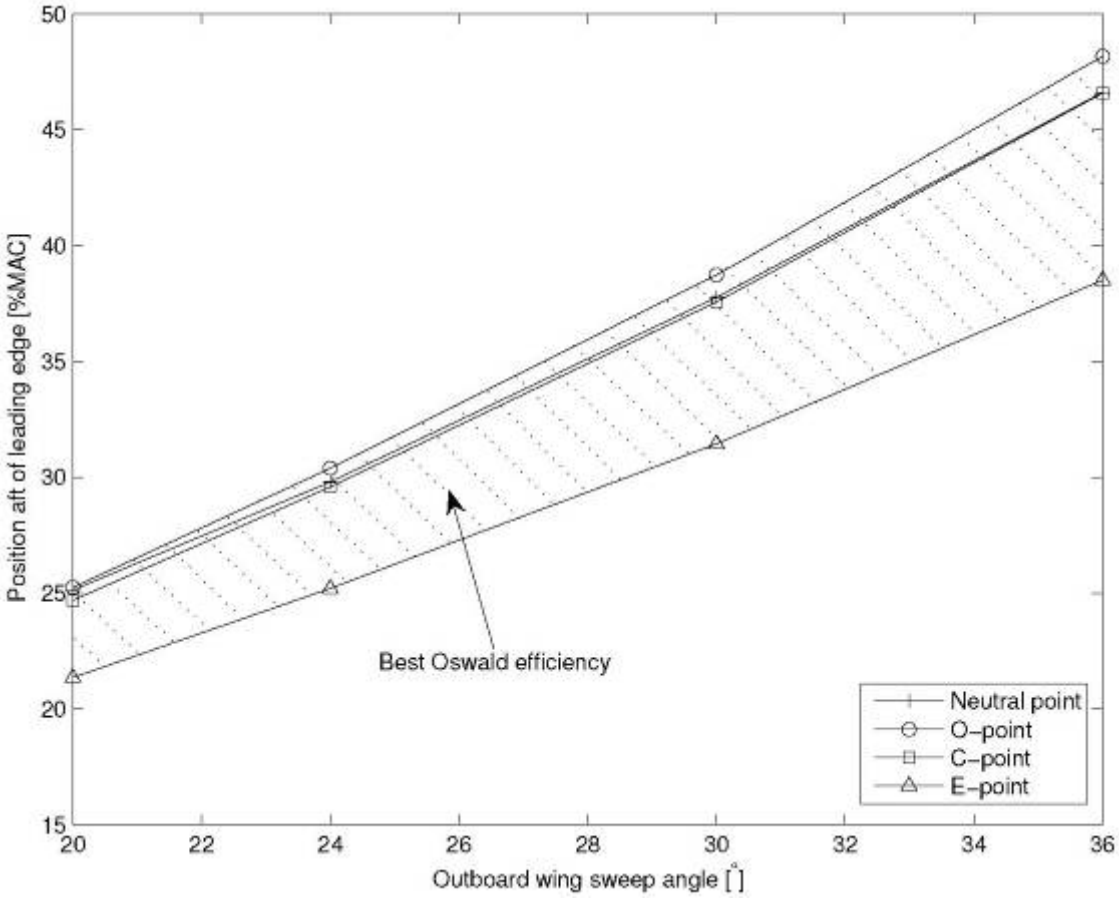


Gull wing planform in this region: Likely to tumble.



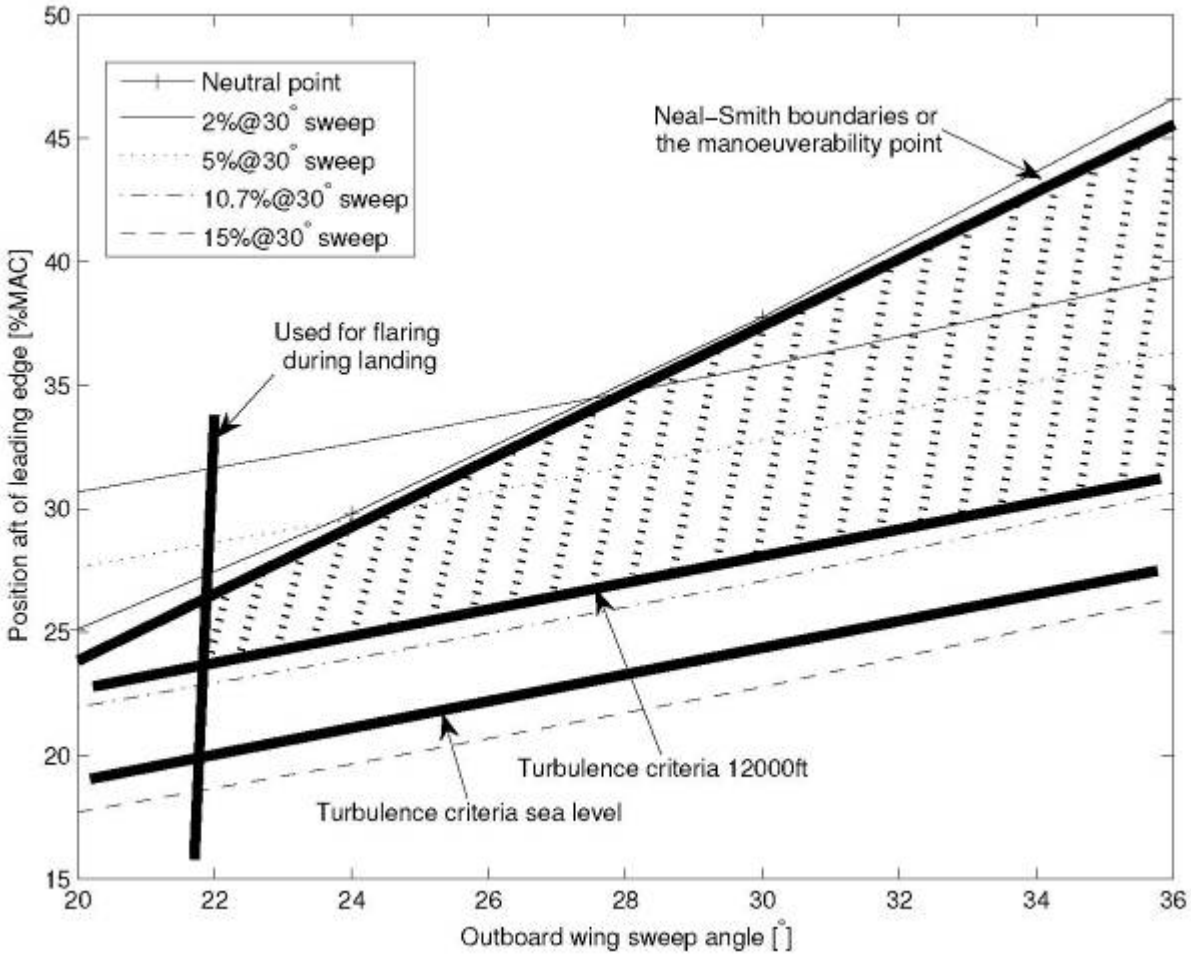
Summary of results

- Region of best Oswald efficiency



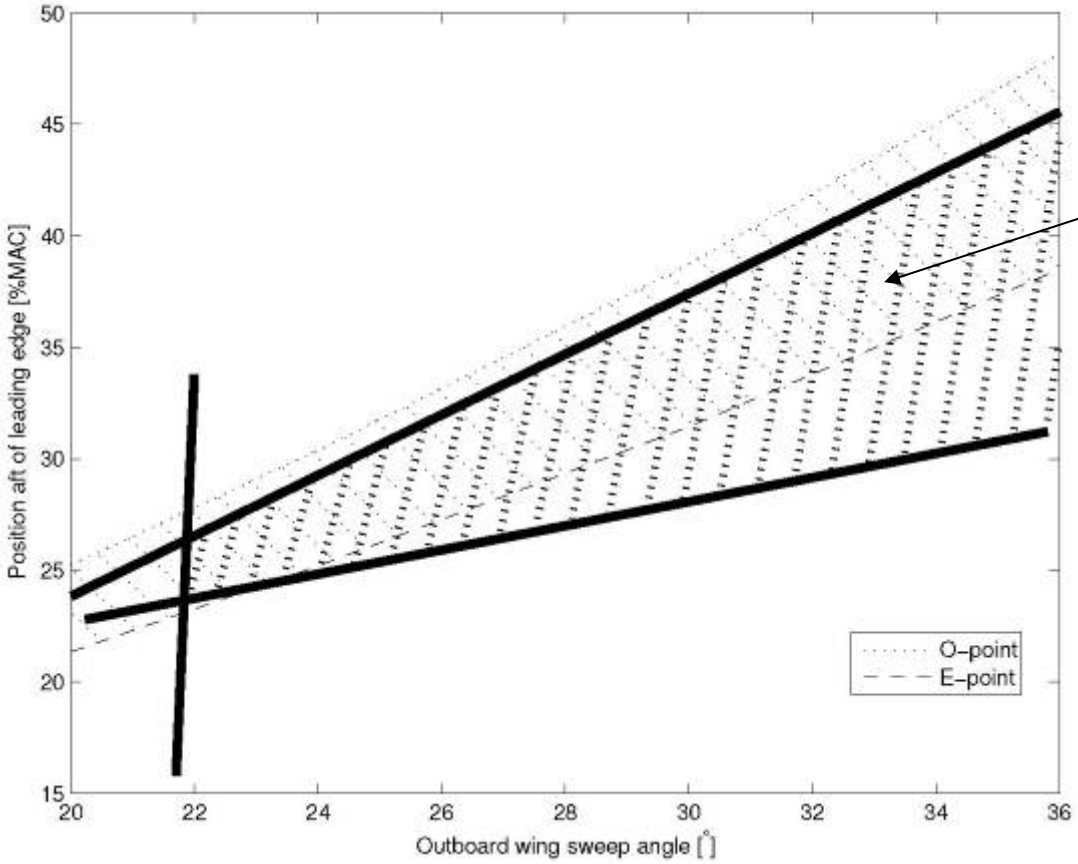
Summary of results

- Region of most favourable handling qualities



Summary of results

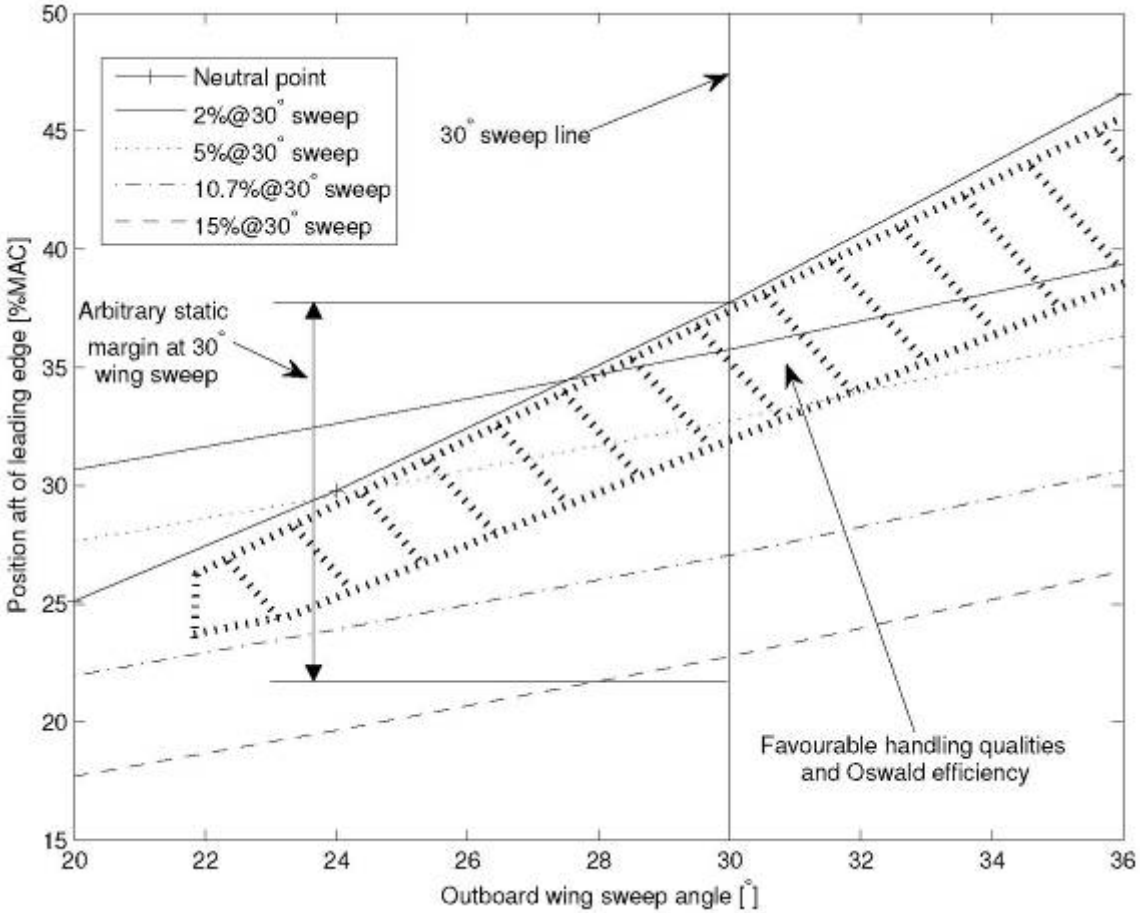
- Superimpose region of good handling quality with region of best Oswald efficiency



Overlapping region

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