Worst-case Gust Loads Analysis in the Presence of Non-linearity

Final MSc Dissertation

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Introduction

Predominant practice

Aircraft design is limited to a linear and deterministic regime, in spite of rapidly increasing demands to consider unavoidable non-linearity

New framework for

Investigation of the influence of structural non-linearities on worst-case gust loads predictions
Introduction

Worst-case gust loads

Input parameters + Dynamic gusts

Linear aeroelastic model

IQs (shear force, bending moment, torque...)

Critical load values!

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Introduction

Non-linearity

Sources

How does non-linearity affect the worst-case gust loads that are being predicted?

Is it necessary to include non-linearity in these phases of the design?

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Previous work

2-D gust model

\[ A\ddot{q} + [D + \rho VB]\dot{q} + [E + \rho V^2 C]q + f_{NL}(\dot{q}, q) = \mathbf{w}_g(t) \]

Generalized response vector
Aerodynamic response-dependent matrices
Non-linear restoring force function

Inertia matrix
Structural damping matrix
Vector of time-dependent wind gusts

Structural stiffness matrix

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3-D Goland Wing model

\[ M\ddot{\xi} + D\dot{\xi} + K\xi + f_{NL} = F_{Aero} \]

- Generalized coordinates vector
- Structural stiffness matrix
- Aerodynamic forces
- Mass matrix
- Damping matrix
- Non-linear restoring force function

\[ K_x, K_y, K_z, K_{rx}, K_{ry}, K_{rz} \]
3-D Goland Wing model

DLM + RFA

\[ M \dddot{\xi} + D \dddot{\xi} + K \dot{\xi} + f_{NL} = F_{Aero} \]

\[
F_{Aero} = \frac{1}{2} \rho U^2 \left\{ \begin{array}{c}
Q_{hh0} \dddot{\xi}_h + \frac{c}{2V} Q_{hh1} \dot{\xi}_h + \left( \frac{c}{2V} \right)^2 Q_{hh2} \dddot{\xi}_h \\
+ \left[ Q_{hj0} \omega_j + \frac{c}{2V} Q_{hj1} \dot{\omega}_j + \left( \frac{c}{2V} \right)^2 Q_{hj2} \dddot{\omega}_j \right] + \sum_{l=1}^{N_{Poles}} R_l \end{array} \right\}
\]

GAF matrix related to generalized coordinates

GAF matrix related to the gust

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Gust loads

Discrete 1-cos Gust

\[ M \ddot{\xi} + D \dot{\xi} + K \xi + f_{NL} = F_{Aero} \]

\[ w_j = \cos \gamma_j \frac{w_{g0}}{2V} \left( 1 - \cos \left( \frac{2\pi V}{L_g} \left( t - \frac{x_0 - x_j}{V} \right) \right) \right) \]

\[ w_{g0} = w_{ref} \left( \frac{H}{106.14} \right)^{1/6} \]
Non-linearity modelling

Cubic non-linear spring with 6 components: X,Y,Z,RX,RY,RZ

\[
M\ddot{\xi} + D\dot{\xi} + K\xi + f_{NL} = F_{Aero}
\]

Spring force function

\[
f_{NLj} = K_{Lj}\Delta j + K_{NLj}(\Delta j)^3
\]

\[
f_{NLz} = K_{Lz}\Delta z + K_{NLz}(\Delta z)^3
\]

\[
f_{NLry} = K_{Lry}\Delta ry + K_{NLry}(\Delta ry)^3
\]
Input parameters

Speed Altitude

Gust length

Mass
Mass modelling

Fuel tank

Assumptions:
\[ W_{Fuel} = 2 \times W_{wing} \]
Wing fuel is 50% of total fuel
General Loads Process

Structural model

Aerodynamic model

K M
Modal Base

GAF
GAF time

Gust

ODE

MPF

Post-process

Loads and Displacement
Results and analysis

Linear:
\[ K_l = [10^8, 10^8, 1.4 \times 10^4, 10^8, 5 \times 10^5, 10^8] \]

Non-linear:
\[ K_l = [10^8, 10^8, 1.4 \times 10^4, 10^8, 5 \times 10^5, 10^8] \]
\[ K_n = [0, 0, 1.4 \times 10^4, 0, 5 \times 10^5, 0] \]

Units: \( K_x, K_y, K_z \) (lbf/ft) \( K_{rx}, K_{ry}, K_{rz} \) (lbf*ft/rad)
Critical cases

Different critical cases!
Levels of non-linearity

Weak non-linearity:
\[ K_l = [10^8, 10^8, 1.4 \times 10^4, 10^8, 5 \times 10^5, 10^8] \]
\[ K_n = [0, 0, 1.4 \times 10^2, 0, 5 \times 10^3, 0] \]

Strong non-linearity:
\[ K_l = [10^8, 10^8, 1.4 \times 10^4, 10^8, 5 \times 10^5, 10^8] \]
\[ K_n = [0, 0, 1.4 \times 10^4, 0, 5 \times 10^5, 0] \]
Conclusions

The results from the previous two academic models show the impact of non-linearity in the critical gust load cases.

Critical cases for the linear model are considerably different from those of the non-linear models. At certain flight points, the critical loads become more extreme.
Future work

Following step: To apply the approach to the full aircraft model.

Main idea: To model the attachments of the pylons of the engines as cubic non-linear springs, as previously done in the Goland Wing model.
Thank you for your attention.
Any questions?