Aeroelastic Gust Response

Civil Transport Aircraft - xxx
Presented By: Fausto Gill Di Vincenzo
04-06-2012
What is Aeroelasticity?

Aeroelasticity studies the effect of aerodynamic loads on flexible structures, taking into account the dependence of the aerodynamic loads on the deformation of the structure and vice-versa.

Standard Analysis available in MSC Nastran (Structure & Aero linear)

- **Static Aeroelasticity (Sol144)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady Aerodynamics</td>
<td>Static Stability Derivatives</td>
</tr>
<tr>
<td>Stiffness Properties</td>
<td>Trim Analysis</td>
</tr>
<tr>
<td>Inertia Properties</td>
<td>Static Loads</td>
</tr>
<tr>
<td></td>
<td>Static Deformations</td>
</tr>
</tbody>
</table>

- **Flutter (Sol145)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillatory Aerodynamics</td>
<td>Flutter Analysis</td>
</tr>
<tr>
<td>Structural Stiffness</td>
<td>Dynamic Stability Derivatives</td>
</tr>
<tr>
<td>Inertia Properties</td>
<td></td>
</tr>
<tr>
<td>Control System (Optional)</td>
<td></td>
</tr>
</tbody>
</table>

longitudinal Trim Analysis

Stability Margin - Root Locus
What is Aeroelasticity?

Aeroelasticity studies the effect of aerodynamic loads on flexible structures, taking into account the dependence of the aerodynamic loads on the deformation of the structure and vice-versa.

**Standard** analysis available in MSC Nastran (Structure & Aero linear)

- **Dynamic Aeroelasticity (Sol146)**
  
<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillatory Aerodynamics</td>
<td>Frequency Response</td>
</tr>
<tr>
<td>Structural Stiffness</td>
<td>Transient Response</td>
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<tr>
<td>Inertia Properties</td>
<td>Random Response</td>
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<td>Control System (optional)</td>
<td>Dynamic Loads</td>
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<tr>
<td>Excitation</td>
<td></td>
</tr>
</tbody>
</table>

- **Design Sensitivity and Optimization (Sol200)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Aeroelastic and / or Flutter Input</td>
<td>Resized Structure</td>
</tr>
<tr>
<td>Design Model</td>
<td>Analysis Results</td>
</tr>
<tr>
<td>1. Objective</td>
<td></td>
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<tr>
<td>2. Constraints</td>
<td></td>
</tr>
<tr>
<td>3. Design Variables</td>
<td></td>
</tr>
</tbody>
</table>

**Civil Transport Aircraft – Gust Response**

**Structural Modal tuning**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Exp [Hz]</th>
<th>Num [Hz]</th>
<th>Error [%]</th>
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<tbody>
<tr>
<td>First</td>
<td>9.60</td>
<td>9.5683</td>
<td>0.33</td>
</tr>
<tr>
<td>Second</td>
<td>38.10</td>
<td>38.109</td>
<td>0.02</td>
</tr>
<tr>
<td>Third</td>
<td>50.70</td>
<td>50.836</td>
<td>0.27</td>
</tr>
<tr>
<td>Fourth</td>
<td>98.50</td>
<td>98.672</td>
<td>0.17</td>
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</tbody>
</table>
What is Aeroelasticity?

Aeroelasticity studies the effect of aerodynamic loads on flexible structures, taking into account the dependence of the aerodynamic loads on the deformation of the structure and vice-versa.

**Non Standard** FSI analysis available in MSC Nastran OpenFSI (Structure & Aero linear or nonlinear)

- **Transient Dynamic Aeroelasticity (Sol400)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsteady Aerodynamics</td>
<td>Transient Response</td>
</tr>
<tr>
<td>Structural Stiffness</td>
<td>Dynamic Loads</td>
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<tr>
<td>Inertia Properties</td>
<td></td>
</tr>
<tr>
<td>Control System (optional)</td>
<td></td>
</tr>
<tr>
<td>Excitation</td>
<td></td>
</tr>
</tbody>
</table>

- **Non linear Dynamic Aeroelasticity (Sol400)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsteady Aerodynamics</td>
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</tr>
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MSC Software

Simulating Reality, Delivering Certainty
Topics

Standard Aeroelastic Gust Response - Sol146

- Civil Transport Aircraft - Gust Load Certification
  - Deterministic approach - Discrete Gust
  - Stochastic approach - Continuous Turbulence
    - Static Aeroelastic Analysis with CFD data for Steady 1-g Load condition (UAV) - Sol144

Advanced Aeroelastic Gust Response - Sol400 UVLM.OpenFSI

- Unmanned Aerial Vehicle
  - Structural Dynamic Optimization - Sol200
  - Discrete Gust Response at Trim Flight condition
  - Aeroelastic Gust Response with Control System
Aeroelastic Model Creation

Civil Transport Aircraft - xxx

Structural Stick Model

Aerodynamic Model
Aeroelastic Model Creation

Structural-Aero Coupling

Inboard Wing Coupling
Aeroelastic Model Creation

Structural-Aero Coupling

Outboard Wing Coupling

From Structural and Aerodynamic models
Civil Transport Aircraft Certification

Aeroelastic Model

Aerodynamics given by DLM (Potential theory - Lifting surface)

Mode # 27 - 32.38 Hz

Mode # 39 - 49.56 Hz
Civil Transport Aircraft Certification

Structural-Aero Coupling

Mode # 4 - 1.62 Hz
Civil Transport Aircraft Certification

Structural-Aero Coupling

Mode # 6 - 5.4 Hz
Solution - SPLINE Verification

Structural-Aero Coupling

Mode # 7 - 6.3 Hz
Certification Specification for Large Aeroplanes

CS 25.341 - Gust and turbulence loads

There are two methods widely accepted by the aeronautical authorities. Dynamic gust load conditions applied to aircraft consist of discrete gust and continuous turbulence (or continuous gust)

• **Deterministic approach (Discrete gust)**

  The deterministic method describes the “worst case” atmospheric gust approach. For discrete gust loads the atmospheric turbulence is assumed to have one-minus-cosine velocity profile that can be described as a function of time. Response and load time history correspond to solutions of the airplane equation of motion in time domain.

• **Stochastic approach (Continuous turbulence)**

  For continuous gust loads, the atmospheric turbulence is assumed to have a Gaussian distribution of gust velocity intensities that can be specified in the frequency domain as a power spectral density (PSD) function.

For both methods a set of gust velocities for specific flight conditions has been defined. From several types of gust PSD functions the Von Kármán and Dryden function are widely used.
Tasks of the Simulation

• **Aeroelastic Model Creation**
  • Aerodynamic Model DLM
  • Aero-Structure Coupling - Splining Check

• **Compute the Gust Response**
  • Tuned Discrete Gust (TDS) - One-minus-cosine Gust model

• **Results of interest**
  • Acceleration over the Wing
  • Wing Root Bending Moment
Civil Transport Aircraft Certification

The Aircraft has to be able to withstand the Dynamic Gust Load

- **Deterministic approach** - Discrete Gust (Time domain)

![Sketch of discrete gust load](image)
Deterministic approach - Discrete Gust Definition

\[ U = \frac{U_{ds}}{2} \left[ 1 - \cos\left(\frac{\pi s}{H}\right) \right] \]

**CS 25.341  Gust and turbulence loads**

(See AMC 25.341)

(a) *Discrete Gust Design Criteria.* The aeroplane is assumed to be subjected to symmetrical vertical and lateral gusts in level flight. Limit gust loads must be determined in accordance with the following provisions:

1. Loads on each part of the structure must be determined by dynamic analysis. The analysis must take into account unsteady aerodynamic characteristics and all significant structural degrees of freedom including rigid body motions.

2. The shape of the gust must be taken as follows:

\[ U = \frac{U_{ds}}{2} \left[ 1 - \cos\left(\frac{\pi s}{H}\right) \right] \quad \text{for } 0 \leq s \leq 2H \]

\[ U = 0 \quad \text{for } s > 2H \]

where –

- \( s \) = distance penetrated into the gust (metre);
- \( U_{ds} \) = the design gust velocity in equivalent airspeed specified in sub-paragraph (a) (4) of this paragraph;
- \( H \) = the gust gradient which is the distance (metre) parallel to the aeroplane’s flight path for the gust to reach its peak velocity.

- Uds - Maximum Gust Velocity
- H - Gust Gradient Length
- L/2 - Half length of Gust
- s - Distance into the Gust

\[ U = \frac{U_{ds}}{2} \left[ 1 - \cos\left(2\frac{\pi s}{L}\right) \right] \]
Deterministic approach - Discrete Gust Definition

\[ U = \frac{U_{ds}}{2} \left[ 1 - \cos\left(\frac{2\pi s}{L}\right) \right] \]

(6) The flight profile alleviation factor, \( F_a \), must be increased linearly from the sea level value to a value of 1.0 at the maximum operating altitude defined in CS 25.1527. At sea level, the flight profile alleviation factor is determined by the following equation.

\[ F_a = 0.5 \left( F_{\text{ms}} + F_{\text{em}} \right) \]

where:

\[ F_{\text{ms}} = \frac{Z_{\text{ms}}}{76200} \quad (F_{\text{ms}} = 1 - \frac{Z_{\text{ms}}}{250,000}) \]

\[ F_{\text{em}} = \sqrt{R_2 \tan \left( \frac{\pi R}{4} \right)} \]

\[ R_1 = \frac{\text{Maximum Landing Weight}}{\text{Maximum Take-off Weight}} \]

(3) A sufficient number of gust gradient distances in the range 9 m (30 ft) to 107 m (350 ft) must be investigated to find the critical response for each load quantity.

\[ H \in \left[ 30 \text{ ft} \div 350 \text{ ft} \right] = \left[ 360 \text{ in} \div 4200 \text{ in} \right] \]

\[ 2H = L = 1171.30 \text{ in} \quad (\text{Aircraft Length}) \]

- Altitude - Sea level
- True Air Speed - 6886.36 in/s

\[ M_{\text{TOW}} = 104700 \text{ lb} \]
\[ M_{\text{FW}} = 51800 \text{ lb} \]
\[ O_{\text{WE}} = 62500 \text{ lb} \]
\[ M_{\text{LW}} = 84800 \text{ lb} \]
\[ Z_{\text{mo}} = 32275 \text{ ft} \]

\[ U_{ds} = 29.75 \text{ ft/s} = 356.75 \text{ in/s} \]
Problem Data

- Flight Velocity: 6886.36 in/s
- Speed of sound: 13512 in/s (1126 ft/s)
- Mach Number: 0.51
- Air Density: 1.1468E-7 pound*in/in^3
- Reference Chord: 170 in
- Gust length: 1171.30 in
- Gust Amplitude Uds: 356.97 in/s
- Simulation time: 3 s
- \( \Delta x = 0.08 \times \frac{V}{F_{\text{max}}} \): 11 in
- \( \Delta f \): 0.01 Hz
Guideline

• Determine the frequency range to be considered.
• Determine the number of modes to be used.
• Use enhanced modal reduction with a residual vector generated for the response degree of freedom.
• Determine the reduced frequencies at which aerodynamic matrices are to be computed.
• Take care of the rigid body motion
Compute the Gust response

Translational Displacement – Side View

Translational Displacement – Front View
Results - Tip Displacement

Max Wing Tip Deflection

Max ≈ 25.3 in (0.64 m)

Node 2064
Results - Acceleration

Nz @ Node 2001

Max ≈ 0.497 g

Min ≈ -0.510 g
Results - Acceleration

Max ≈ 0.587 g
Min ≈ -0.648 g
Results - Acceleration

Nz @ Node 2025

Normal Load Factor

Max ≈ 1.271 g

Min ≈ -0.724 g

Time [s]
Results - Acceleration

Nz @ Node 2064

Normal Load Factor

Max ≈ 13.04 g
Min ≈ -18.61 g
Results - Acceleration over the Wing

Getting the Maximum of the Aeroelastic response over the wing

Positive Normal Load Factor - Nz (Max)

13.04 g
1.271 g
0.587 g
0.497 g
Results - Forces

Bending Moment @ Station#1 - Nz (Max)

Max ≈ 453391 N-m

Min ≈ -393991 N-m
Civil Transport Aircraft Certification

The Aircraft has to be able to withstand the Dynamic Gust Load

- **Stochastic approach** - Continuous Turbulence (Frequency domain)
Tasks of the Simulation

• Compute the Gust Response
  • Power Spectral Density (PSD) - Von Kármán function

• Results of interest
  • PSD Acceleration of Wing Root
  • PSD Bending Moment of Wing Root
Continuous Turbulence Design Criteria

\[ \Phi_T(\Omega) = \frac{L}{\pi} \frac{8}{3} \frac{(1.339\Omega L)^2}{[1 + (1.339\Omega L)^2]^{1/6}} \]

CS 25.341  Gust and turbulence loads
(See AMC 25.341)

(b) Continuous Turbulence Design Criteria. The dynamic response of the aeroplane to vertical and lateral continuous turbulence must be taken into account. The dynamic analysis must take into account unsteady aerodynamic characteristics and all significant structural degrees of freedom including rigid body motions. The limit loads must be determined for all critical altitudes, weights, and weight distributions as specified in CS 25.321(b), and all critical speeds within the ranges indicated in subparagraph (b)(3).

(1) Except as provided in subParagraphs (b)(4) and (b)(5) of this paragraph, the following equation must be used:

\[ P_L = P_{L-1g} \pm U\sigma \bar{A} \]

- Normalized gust intensity, \( \bar{A} \)

\[ \bar{A} = \frac{\sigma_x}{\sigma_w} \]

- Characteristic frequency, \( N_0 \)

\[ N_0 = \sqrt{\frac{\int_0^\infty \omega^2 \phi_x(\omega)d\omega}{\int_0^\infty \phi_x(\omega)d\omega}} \]

- RMS of any response variable, \( \sigma_x \)

\[ \sigma_x = \sqrt{\int_0^\infty \phi_x(\omega)d\omega} \]
Continuous Turbulence Design Criteria

(b) Continuous Turbulence Design Criteria. The dynamic response of the aeroplane to vertical and lateral continuous turbulence must be taken into account. The dynamic analysis must take into account unsteady aerodynamic characteristics and all significant structural degrees of freedom including rigid body motions. The limit loads must be determined for all critical altitudes, weights, and weight distributions as specified in CS 25.321(b), and all critical speeds within the ranges indicated in subparagraph (b)(3).

1. Except as provided in subparagraphs (b)(4) and (b)(5) of this paragraph, the following equation must be used:

\[ A = \sqrt{\int_0^\infty |H(\Omega)|^2 \Phi_r(\Omega) d\Omega} \]

- \( \Phi_r(\Omega) \) = normalised power spectral density of atmospheric turbulence given by

\[ \Phi_r(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3} (1.339\Omega L)^2}{[1 + (1.339\Omega L)^2]^{1/2}} \]

Where:
- \( \Omega \) = reduced frequency, rad/ft; and
- \( L \) = scale of turbulence = 2,500 ft.

- \( H(\Omega) \) = the frequency response function, determined by dynamic analysis, that relates the loads in the aircraft structure to the atmospheric turbulence

2. \[ U_\sigma = U_{\sigma_{\text{ref}}} F_g \]

- \( F_g \) = the flight profile alleviation factor defined in sub-paragraph (a)(6) of this paragraph.
- \( U_{\sigma_{\text{ref}}} \) is the reference turbulence intensity (90 ft/s) (TAS) at sea level
Effect of L on Von Kármán PSD

\[ \Phi_l(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3} (1.339 \Omega L)^2}{[1 + (1.339 \Omega L)^2]^{1/6}} \]

Von Kármán Spectrum Density

PSD (m/\text{sec})^2/(\text{Cycle/ft})

\(\Omega\) (cycles/ft)
Continuous Turbulence Design Criteria

\[ \Phi_f(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3} (1.339\Omega L)^2}{[1 + (1.339\Omega L)^2]^{1/6}} \]

PSD of Turbulence

Normalized Von Karman PSD

- L = 2500 (ft)
- WG = 1 (ft/s)

Frequency [Hz] vs. PSD [m^2/Hz]
## Problem Data

- **Flight Velocity**: 6886.36 in/s
- **Speed of sound**: 13512 in/s (1126 ft/s)
- **Mach Number**: 0.51
- **Air Density**: 1.1468E-7 pound*sec/in/in^3
- **Reference Chord**: 170 in
- **Scale of Turbulence**: 30000 in (2500) ft
- **Frequency Range**: 0-60 Hz
- **Δx=0.08*V/Fmax**: 11 in
- **Δf**: 0.01 Hz
Results - PSD Acceleration

Nz @ Node 2001

F06 Output Extract

RMS

$N_0$

Vertical Acceleration [g^2/Hz]

Frequency [Hz]

$\bar{A} = \frac{\sigma_x}{\sigma_w}$

$\bar{A} = \frac{8.8568 \text{ in/s}^2}{12 \text{ in/s}} = 0.738 \text{s}^{-1}$

$A_z = U_\sigma \bar{A} = 0.738 \text{s}^{-1} \cdot 66.42 \text{ ft/s} = 49.018 \text{ ft/s}^2$

$N_z = \frac{A_z}{g} = \frac{49.018 \text{ ft/s}^2}{32.174 \text{ ft/s}^2} = 1.52g$
Results - PSD Acceleration

Nz @ Node 2007

Incremental Load

Normal Load Factor

\[ P_L = P_{L-\text{ig}} + U_{\sigma A} \]

\[ Nz_L = 1.31g \]
Displayed is a graph showing the Normal Load Factor as a function of frequency. The graph indicates the vertical acceleration (g/Hz) and frequency (Hz) for a specific node labeled "Node 2025." The incremental load is denoted as: \[ P_L = P_{L-15} \pm U_{A} \]

The normal load factor is calculated to be: \[ N_{ZL} = 1.69g \]
Results - PSD Acceleration

Nz @ Node 2001

Normal Load Factor

\[ N_{zL} = 14.82g \]

Incremental Load

\[ P_L = P_{L-15} \pm U \sigma A \]
Results - Acceleration over the Wing

Getting the Dynamic Load Increment over the wing

Normal Load Factor - Nz (Max)

14.82 g

1.69 g

1.52 g

1.31 g
Results - PSD Vertical Bending Moment

**Wing Root Bending Moment**

- **Static Load**: $P_L = P_{L-1g} \cdot U_{OA}$
- **Incremental Dynamic Load**: $BM_{VL} = 651507lb - f = 883313N - m$
Solution needs a high fidelity approach to get the 1-g steady state

MSC Software has developed an advanced capability to use CFD aerodynamic pressure in Sol144

Hybrid Static Aeroelastic Solution with CFD data - Sol144
Advanced Aeroelastic Solution - Sol400 OpenFSI

Transient Longitudinal Maneuver Analysis without Control System - UAV

- Pilot input command - Control surface
- MSC Nastran UVLM.OpenFSI.RESTART functionality
- Starting point for AeroServoElasticity (ASE).

Transient Longitudinal Trim Analysis with Control System - UAV

- Elevator Control system
- MD Nastran UVLM.OpenFSI.RESTART functionality
- Comparison with standard solution

Transient Gust Response Analysis with Control System - UAV

- Elevator Control system
- MD Nastran UVLM.OpenFSI.RESTART functionality
- Comparison with standard solution

Non Linear Aeroelastic Analysis - Non conventional Aircraft HALE

- MSC Nastran Large Displacement Capability
Aerodynamic Code - UVLM

- Geometric nonlinearity at subsonic flows
- Time domain aeroelastic simulation
- Free wake formation
- Lift due to vortex roll up at high angle of attack
- Aeroelastic response due to 1-D/2-D discrete gust and pilot input command
- Cp distribution from Tunnel test or CDF
- Stall modeling by strip method
- Airfoil definition – NACA series or user defined
- Aerodynamic body modeling
- Aerodynamic blade component
Transient Longitudinal Maneuver Analysis without C.S.

\[ \alpha = 2.73^\circ \quad \delta_E = -2.5^\circ \]

- Vertical displacement of the UAV center of mass
- Overall vertical aerodynamic load vs UAV weight

- No Control System \( \rightarrow \) The UAV is not balanced \( \rightarrow \) Altitude lost about 1.34 m
- Structural and Aerodynamic solution stored \( \rightarrow \) RESTART Analysis

6/5/2012
Transient Longitudinal Maneuver Analysis

- Structural and Aerodynamic data recovered from the previous FSI simulation ($\delta_E = -2.5^\circ$)
- Aeroelastic response to a Pilot Input Command on the Elevator

**Vertical displacement of the UAV center of mass**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>5.0</th>
<th>5.4</th>
<th>5.8</th>
<th>6.2</th>
<th>6.6</th>
<th>7.0</th>
<th>7.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-Displacement [m]</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

**Time history of the pilot input command - Elevator**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>5.1</th>
<th>5.9</th>
<th>6.1</th>
<th>6.9</th>
<th>7.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

- It is possible to evaluate the aeroelastic response delay to a control surface input
  - TRIM algorithm
  - Control system

Comparison with standard gust response Sol146
Transient Longitudinal Maneuver Analysis without C.S.

\[ \alpha = 2.73^\circ \quad \delta_E = -2.5^\circ \]

- Wake formation
  - The free wake is part of the solution
  - The aerodynamic mesh deforms with the structure

Vortex Tip Rollup

Free vortex wake propagation
Transient Longitudinal Trim Analysis with Control System

Aerodynamic load components - Reference cord system

Load Balance

TRIM algorithm developed in python

- Control System on the Elevator
  - Translational Balance within X direction
  - Translational Balance within Z direction
  - Rotational Balance along Y axis

\[
\begin{align*}
\sum F_z &= 0 \\
\sum M_y &= 0 \\
\sum F_x &= 0
\end{align*}
\]

Dynamic of Flight equations to be satisfied
Transient Longitudinal Trim Analysis with Control System

Aerodynamic overall Load - $F_z$

$\sum F_z, \sum F_x = 0$

Translational balance is satisfied!
Transient Longitudinal Trim Analysis with Control System

\[ \sum M_y = 0 \quad \text{Rotational balance along } y \text{ is satisfied} \]
\[ \sum M_y, \sum F_z, \sum F_x = 0 \quad \text{All Dynamic of Flight equations are satisfied Trim solution is got!} \]

Structural deformation @ Trimmed condition

It is now possible to perform Gust Analysis!
Transient Gust Response Analysis with Control System

EASA Certification Specification for light Aircraft:

\[ U = \frac{U_{de}}{2} \left( 1 - \cos \frac{2\pi s}{25C} \right) \]

- Ude - Maximum Gust Velocity
- H - Gust Gradient Length
- 25C/2 - Half length of Gust
- s - Distance into the Gust
- C - mean geometric chord

Discrete Gust Profile – 1 - cos

Ude = 15.74 m/s
T = 0.393 s
The Control system makes the UAV get back the trimmed flight condition!
Transient Gust Response Analysis with C.S.

(Structure is linear)

Sol146 and Sol400 are in good accordance

It is possible to take into account for nonlinearities to study Aeroelastic response of structure with large displacement
Transient Gust Response Analysis

The UAV is able to restore the Trim flight condition thanks to the Control System.

It could be possible to act on Airelons to reduce load on Wings. 

Gust Alleviation
Application - Nonlinear Aeroelastic Analysis

MD Nastran Structural Model

UVLM Aerodynamic Model

- Geometry
  - Span of 72.78 m
  - Constant chord of 2.44 m
  - 10 degrees dihedral angle at ends
  - Two pods at 2/3 of from the mid-span 22.69 Kg
  - Central pod weighs 254 Kg.
  - Overall weight of about 952.53 Kg

- Aerodynamic
  - 12 panels chordwise
  - 30 panels spanwise
  - Vortices shed from trailing edge and wing tip

All six DOFs of the mid-span central section constrained to be zero. Gravity is not considered

- FEM
  - Shells for the wing
  - Solid for pods
Application - **Nonlinear Aeroelastic Analysis**

- **Flight condition**
  - $M = 0.1$ Sea Level
  - Flight cruise velocity 12.5 m/s
  - $\alpha = 16^\circ$

- **Max vertical deflection of about 18 m**
- **No dynamic instability found**

Wake propagation - Ortho view

![Wake propagation - Ortho view](image)

Structural deformation - Front view

![Structural deformation - Front view](image)