Efficient Modelling of a Nonlinear Gust Loads Process for Uncertainty Quantification of Highly Flexible Aircraft

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The *AeroGust* Project

- EU funded Horizon 2020 project
  - Collaboration between industry and academia
- Inspiration from Flight Path 2050
  - Maintaining and extending industrial leadership

Background

- Market trend for adoption of more flexible structures, novel design configurations and higher flight speeds
  - Pushing limits of linear analyses
- Process relies on wind tunnel data from predicted cruise geometry
  - Gust loads considered relatively late in design procedure – design space limited
- Extension of aerospace technologies to wind turbine design
• University of Bristol
• Institut National De Recherche En Informatique Et En Automatique (INRIA)
• Stichting Nationaal Lucht - En Ruimtevaartlaboratorium (NLR)
• Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
• University of Cape Town
• Numerical Mechanics Applications International SA (NUMECA)
• Optimad engineering s.r.l.
• University of Liverpool
• Airbus Defence and Space
• Dassault Aviation SA
• Piaggio Aero Industries SPA
• Valeol SAS
Motivation for this Work

• Understanding what effect structural nonlinearities have on aircraft loads compared to the traditional, industrial approach
  • Particular focus on next-gen HARW
  • Large deformations

• Develop a rapid nonlinear gust loads process for analysis of HARW
  • Subject to atypical gust excitations
  • Use this gust loads process to perform uncertainty quantification
Background
Nonlinear Aeroelastic Framework
Nonlinear Aeroelastic Framework

- Free-free geometrically-exact nonlinear beam code based on Hodges’ intrinsic beam formulation
  - Linear strain-curvature/force-moment relationship
  - Large beam deformations and rotations captured

\[
\begin{bmatrix} M \end{bmatrix} \begin{bmatrix} \dot{V} \\ \Omega \end{bmatrix} + \begin{bmatrix} \dot{\Omega} \\ 0 \end{bmatrix} \begin{bmatrix} M \end{bmatrix} \begin{bmatrix} V \\ \Omega \end{bmatrix} = \begin{bmatrix} F' \\ M' \end{bmatrix} - \begin{bmatrix} \dot{F} \\ \dot{M} \end{bmatrix} + \begin{bmatrix} C \end{bmatrix} \left( \begin{bmatrix} F + e_f \\ M \end{bmatrix} \right) + \begin{bmatrix} f \\ m \end{bmatrix}
\]

- Additional equation required to satisfy free-free conditions
  - Free-free velocity couples with second equation above
  - Allows for arbitrarily large rigid body rotations
  - Linear finite-elements are used to solve the structural EOM
  - Positions and orientations are obtained by integrating strains/curvatures along the beam, or, velocities with time (parameterising rotations using quaternions
Nonlinear Aeroelastic Framework

- Aerodynamics from modified unsteady strip theory
  - Leishman’s indicial response method for unsteady effects (compressibility effects ignored)
  - Spanwise lift distribution from VLM
  - Sectional AoA related to beam motion
  - Linear relationship between AoA and lift (no stall)

- Static coupled nonlinear structural and aerodynamics equations solved using Newton-Raphson method

- Dynamic solution obtained using Newmark-β time-stepping solver

- Code verified against Nastran, other UoB codes, UCT, UMich, UoC
Gust Loads Process
Gust Loads Process for NL Aeroelastics

- Industrial gust loads process can no longer be used for NL system
- Large deformations may lead to RTC gusts exceeding a purely vertical or lateral gust
  - RTC gusts cannot be calculated directly for NL system
- Atypical gusts should also be included (oblique gusts)
Gust Loads Process for NL Aeroelastics

- Oblique gusts add an effective delay and asymmetry to the loading
- Future work could consider other type of gust excitation
Gust Loads Process for NL Aeroelastic:

- Potentially huge numbers of simulations required to cover all gust excitation parameters for NL system – especially if considering atypical gusts.
- Linearisation of aeroelastic equations gives good qualitative comparison to NL.
- Monte Carlo simulations of possible gust excitation parameters on the linear system are used, combined with neural network surrogate models:
  - Map from gust parameters to max/min loads
  - Use NN to find worst case gust excitation.
Identifying worst case gusts

- NN fitted to MCS of linearised system
- Gust case which results in largest loads determined

- Worst gust cases determined for all loads directions for all wing elements
- Subset of cases determined from whole problem space
  - RTC gust angle calculated as post-process
Uncertainty Quantification
Uncertainty Quantification Methods

• Gust loads process can be expressed as a black-box-type “block”

\[ Y = f(X) \]

• Aim of UQ is to determine how uncertainties in input variables propagate through the mapping
• MCS could be considered, but results in an unfeasibly large number of simulations
• Polynomial chaos expansion methods are used to reduce number of simulations
  • Fitting Hermite polynomials to samples of data reduces number of simulations required
Uncertainty Quantification

- Need to define what system inputs are uncertain
  - Environmental uncertainties (air density, temperature, etc.)
  - Aircraft property uncertainties (stiffness properties, mass properties, etc.)
  - Gust inputs themselves are assumed to be the known, EASA/FAA regulation deterministic input gusts

- Need to define reasonable input PDFs for the uncertain variables
  - Little information found in literature for what values to use
  - Initial results use a normal distribution with 3σ limits at ±10% of the mean values

- Young’s modulus (and shear modulus) will be considered to be uncertain in this work
Test Case
HARW Test Case

- HARW baseline structure sized on static manoeuvres
  - Inspired by similar size/AR aircraft considered in research
- Stiffness properties obtained from wing box sections
  - Thicknesses determined to minimise weight while not exceeding stress limits
- One flight and mass case considered
  - Mach 0.7 10,000m altitude
  - Half fuel mass case (69,400kg)

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<th>Wing</th>
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<td>Tip Thickness-Chord Ratio</td>
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Results
PCE Convergence Study
Convergence Studies

- Monte Carlo based methods are commonly used to verify what PCE order and number of samples is appropriate
  - A minimum number of samples is known
- Gust loads process too expensive to carry out with a MCS
  - Even considering the efficient method presented here
- Consideration of a single gust length is feasible to carry out a MCS for verification purposes
- 1,000 simulations on the same gust length are run with varying Young’s modulus
  - Loads time histories are enveloped
  - Considered to provide the ‘true’ statistical output properties
PCE Convergence Study – PCE Order Study

Some PDFs predicted well by 1st order PCE. Root in-plane shear and bending are highly skewed – require a higher order.
PCE Convergence Study – Number of Samples

3rd order PCE are selected with various sample numbers. 10 samples and higher are sufficient to predict most skewed distributions.
Static Results
Trim Results – Wing Deflections

- Wing deflections plotted, accompanied by a shaded area encompassing 99.7% ($\approx 3\sigma$) of the results
- Tip deflection <10% span
  - Linear regime
- Tip deflection uncertainties vary by roughly 10% of the mean value
Trim Results – Angle of Attack Distribution

- Local AoA distribution plotted, accompanied by a shaded area encompassing 99.7% ($\approx 3\sigma$) of the results
- Highest uncertainty for AoA at the root and tip of the wing
- At around 12m span, a point is seen with low uncertainty
  - Corresponds with rigid trim AoA
Trim Results – Loads Distributions

Highest uncertainty in axial loads
Dynamic Results
Dynamic Results – Nonlinear Gust Loads

Surrogate-based gust loads process envelopes exceeds traditional method. Significant uncertainty seen in axial, but also in in-plane shear for surrogate-based approach.
Dynamic Results – Nonlinear Gust Loads
Conclusions

• Efficient gust loads process for NL system presented which includes atypical gust excitations, and used in a UQ analysis

• Uncertainties in geometric IQs are affected by changes in Young’s modulus more than those of loads
  • Axial loads affected more prominently due to strong link to geometry of the deformed wing

• Loads envelopes with atypical gust excitation included shown to exceed ‘traditional’ approach
  • Additional parameterisations can be carried out instead

Future Work

• Extend the study to additional types of gust excitations
  • Spanwise distributions – DARPA-type gust

• Additional uncertain inputs

• Look at more flexible aircraft types
The research leading to this work has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 636053.
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