A Kriging Based Corrected Potential Flow ROM for Gust Load Calculations

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AVIATION, 25–29 June 2018

Hyatt Regency Atlanta, Atlanta, Georgia
Overview

1. Introduction
2. Modelling Approach
3. Fluid Structure Interface
4. Reduced Order Model
5. Test Cases
6. Conclusion
1. Introduction

- Interest in non-linear aeroelasticity continues to grow
- There is a need for efficient modelling solutions
- A wide range of theory has been applied to the problem

- An aeroelastic ROM methodology for gust loads has been developed
  - Correct potential flow results with Kriging\cite{oliver90} models
  - Kriging models supply loads to the structural model
  - Create a range in which predictions are reliable

1. Introduction: Gust Definition

- Standardized 1 – cosine waveform gust:

\[ U = \frac{U_a}{2} \left[ 1 - \cos \left( \frac{\pi l}{H} \right) \right] \]

- Definition as per FAA and EASA regulations
2. Modelling Approach: Fluid

- Full order model – ALE Euler equations
- Gusts application: Split Velocity Method\(^2\)
- Spatial discretisation: MUSCL scheme\(^3\) with the Roe solver\(^4\)
- Temporal integration: Dual time stepping\(^5\)


2. Modelling Approach: Fluid

- Reduced order model – Incompressible potential flow
- Unsteady vortex panel method\(^6\) (UVPM)
- Simulate specific 2D sections along the wing

2. Modelling Approach: Structure

- Linearised governing equation:
  \[ M \cdot \ddot{x} + C \cdot \dot{x} + K \cdot x = f \]
- Temporal integration: Newmark’s Method \([7]\)

- Investigate two structures:
  1. FFAST Crank aerofoil\([8]\) (2D)
  2. NASA Common Research Model\([9]\) (3D)


3. Fluid Structure Interface (FSI)

- Facilitates coupling of fluid and structure in 3D
- Performs two key functions
  1. Decomposes surface forces onto the beam
  2. Reconstructs the wing surface
- Requires a mapping between surface nodes and beam elements
3. FSI: Mapping

- Split the wing into sections based on the underlying beam elements
- Surface nodes in a section are mapped to the corresponding beam element
3. FSI: Force Decomposition

- Method of McGuire, et. al.\cite{McGuire2000} is used to decompose forces
- Split the surface forces into equivalent force-moment pairs
- Apply force-moment pairs at beam nodes

\[ f_{\text{aero}} \]
\[ f_L \]
\[ f_R \]
\[ m_L \]
\[ m_R \]

3. FSI: Surface Reconstruction

- Cubic splines are fitted through the deformed beam nodes
- The surface is reconstructed around the splines such that
  1. cross-sections are preserved and orthogonal to the spline
  2. twist about the beam axis is accounted for
3. FSI: Surface Reconstruction
4. Reduced Order Model

- Multiple UVPM simulations linked to Kriging models of forces and moments
  - UVPM simulations provide a physical basis
  - Kriging models “correct” the UVPM load estimates

- Interpolate results between two bounding cases
  - Increases training cost
  - Creates a range where predictions are reliable
4. Reduced Order Model

\[ \begin{align*}
&U \\
&\text{with Gust} \\
&\text{without Gust} \\
&\text{with Gust} \\
&\text{with Gust} \\
&\text{with Gust} \\
\end{align*} \]
4. ROM: UVPMs

- Multiple sections along the wing
- Two UVPMs per section
  - Only one “sees” the gust
  - Both follow the beam
- The focus is on characterizing the load distribution
- Provide force coefficients to the Kriging models
4. ROM: Kriging Models

- Six individual models (one per force/moment)
- All models take the same inputs:
  1. Nodal initial position, current displacement and velocity
  2. All force coefficients

- Models give force as function of beam length

$$ q = g\left(l_i, x_i, \dot{x}_i, \bar{C}_L, \bar{C}_M, \bar{C}_D, \bar{C}_L^{ng}, \bar{C}_M^{ng}, \bar{C}_D^{ng}\right) $$
4. ROM: Training

1. Collect training data
   - Select two gust cases
   - Simulate both with the full order model
   - Simulate both with the UVPMs (prescribed motion)
4. ROM: Training

2. Train each model Kriging model separately
   • Select an initial set evenly from both cases
   • Iteratively add training points where error is worst
   • Repeat until error tolerances are met
5. Test Cases

• Investigate two structures
  1. FFAST Crank aerofoil – 2D
  2. NASA Common Research Model (CRM) – 3D

• FFAST Crank investigation is complete
  • Uses a simplified ROM

• CRM investigation is incomplete
  • Full order simulations complete
  • Currently training Kriging models
5. Test Cases: FFAST Model

- Flight conditions:

<table>
<thead>
<tr>
<th>Altitude $z$ (m)</th>
<th>Density $\rho_\infty$ (kg.m$^{-3}$)</th>
<th>Pressure $P_\infty$ (kPa)</th>
<th>Mach number $M_\infty$</th>
<th>Flow velocity $U_\infty$ (m.s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10668</td>
<td>0.3806</td>
<td>23.92</td>
<td>0.86</td>
<td>255.1</td>
</tr>
</tbody>
</table>

- Structure: Pitch-Plunge FFAST crank aerofoil (8m chord)
5. Test Cases: FFAST Training

• Gust selection:

<table>
<thead>
<tr>
<th>Gust Half Length (ft)</th>
<th>Gust Amplitude (m)</th>
<th>Gust Amplitude (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>21.336</td>
<td>17.49</td>
</tr>
<tr>
<td>150</td>
<td>45.720</td>
<td>19.85</td>
</tr>
<tr>
<td>250</td>
<td>76.200</td>
<td>21.61</td>
</tr>
<tr>
<td>350</td>
<td>106.680</td>
<td>22.86</td>
</tr>
</tbody>
</table>

• Error tolerances: 0.1% mean error and 0.5% peak error
• Training set sizes: 200 data points
5. Test Cases: FFAST Results (150 ft)
5. Test Cases: FFAST Results (250 ft)
5. Test Cases: FFAST Results (Error)

| Test Case | Gust half length $H$ (ft) | Absolute maximum $|\epsilon|$ (% abs. max.) |
|-----------|---------------------------|------------------------------------------|
| Plunge    | 150                       | 0.481 m                                  |
|           | 250                       | 0.583 m                                  |
| Pitch     | 150                       | 2.99°                                    |
|           | 250                       | 3.76°                                    |
5. Test Cases: FFAST Computational Cost

- Per run costs:
  - CFD – 90 CPU hours each (1.0 unit)
  - ROM – 2.3 CPU hours each (0.026 unit)
  - Speed up factor – 39

- Total costs (incl. training):
  - 4 CFD runs: 360 CPU hours (4.0 units)
  - 2 CFD runs + 2 ROM runs: 185 CPU hours (2.055 units)
  - Cost Reduction – 49%
5. Test Cases: CRM Model

- Flight conditions:

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<th>Altitude (z (m))</th>
<th>Density $\rho_\infty$ (kg.m$^{-3}$)</th>
<th>Pressure $P_\infty$ (kPa)</th>
<th>Mach number $M_\infty$</th>
<th>Flow velocity $U_\infty$ (m.s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9142</td>
<td>0.4593</td>
<td>30.17</td>
<td>0.86</td>
<td>260.8</td>
</tr>
</tbody>
</table>

- Structure: Condensed MTOW FERMAT FEM Model \cite{Klimmek2014, Wales2017}

- Gust Selection:

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<th>Gust Amplitude (m.s$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td>9.114</td>
<td>11.26</td>
</tr>
<tr>
<td>150</td>
<td>45.720</td>
<td>14.72</td>
</tr>
<tr>
<td>350</td>
<td>106.680</td>
<td>16.96</td>
</tr>
</tbody>
</table>


5. Test Cases: CRM Results (30 ft)
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5. Test Cases: CRM Results (350 ft)
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6. Conclusion

- A novel ROM strategy has been proposed
- The 2D ROM showed good accuracy and substantial speed-up
  - Worst mean and maximum errors of 1.9% and 8.1%
  - Reduced overall cost by 49%
- There is still a need for 3D validation
- Despite this, the approach appears viable
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.