Low-order Aeroelastic Modelling of Highly-Deformable Wings

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http://www.imperial.ac.uk/aeroelastics
• The context → Building ever more efficient aircraft (larger, lighter)

• Multidisciplinary analysis:
  o Structures
  o Aerodynamics
  o Flight dynamics
  o Controls
  o Failure analysis, power management...

• Non-linear flight dynamics of flexible aircraft

• Reduced-order models

• Conclusions and future directions
The challenge of very high efficiency
• A systems integration problem...
“Key recommendations include:

• Develop more advanced, multidisciplinary (structures, aeroelastic, aerodynamics, atmospheric, materials, propulsion, controls, etc) “time-domain” analysis methods appropriate to highly flexible, “morphing” vehicles.

• For highly complex projects, improve the technical insight using the expertise available from all NASA Centers.

• Develop multidisciplinary (structures, aerodynamic, controls, etc) models, which can describe the nonlinear dynamic behavior of aircraft modifications or perform incremental flight-testing.”

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Research objectives

• **Understanding** dynamics in operation of very flexible aircraft
  o Multidisciplinary approach
  o Potentially large wing deflections (i.e. nonlinear analysis)

• **Predicting** performance and flight qualities
  o Multiscale approach for full aircraft analysis
  o Evaluation of non-conventional configurations
  o Virtual aircraft test bed for technology evaluation

• **Exploring** the design space
  o Reduced-order models
  o FCS with (geom-nonlinear) structural dynamics

2009 Imperial Aero 3rd–year Group Design Project
Flexible Aircraft Flight Dynamics Simulation

- Material
- Subcomponent detail model
- Homogenised structural dynamics model
- Unsteady vortex-lattice aero model
- Flight conditions
- Pilot / FCS
- Flight dynamics model
- Aeroelastic model
- Static Nonlinear
- Material model
- Structural integrity
- Full-vehicle dynamics
- Linear/Nonlinear
- Stability characteristics
- Flight performance
- Aircraft trim

Diagram showing the flow of processes in flexible aircraft flight dynamics simulation.
Unsteady Aerodynamics

- Material
- Geometry
- Flight conditions
- Subcomponent detail model
- Homogenised structural dynamics model
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- Static Nonlinear
- Material model
- Full-vehicle dynamics
- Aircraft trim
  - Yes
  - No
  - Linearised
  - Structural integrity
  - Flight performance
  - Stability characteristics
  - Linear/Nonlinear
Unsteady Vortex Lattice Method (UVLM)

- Vortex-ring discretization, as Falkner (1946), Katz & Plotkin (2001)
- Potential flow, thin airfoil $\rightarrow$ Low speed flight, attached flow
- 3-D, unsteady, free-wake, interference, large (but slow) wing displacements
UVLM: discrete-time formulation

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\[
\begin{align*}
\begin{bmatrix}
\Gamma_b \\
\Gamma_w \\
X_w
\end{bmatrix}^{n+1} &=
\begin{bmatrix}
A & A & 0 \\
B & B^* & 0 \\
C & C^* & D
\end{bmatrix}
\begin{bmatrix}
\Gamma_b \\
\Gamma_w \\
X_w
\end{bmatrix}^n
\begin{bmatrix}
E \\
0 \\
0
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} W^{n+1}
\end{align*}
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Non-penetration boundary condition
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W^{n+1}
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\]

Free-wake: convection, roll up, stretching
UVLM: aerodynamic loads from vorticity distribution

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Unsteady Bernoulli equation

\[
\Delta p^{n+1} = f \left( \Gamma_b^n, \Gamma_b^{n+1}, X_b^{n+1}, W^{n+1} \right)
\]
3-D effects in unsteady aerodynamics*

- UVLM vs. thin strip aero

- Prescribed Kinematics

\[ w(y, t) = Ay^2 \cos(\omega t) \]

- Investigate effect of
  - Aspect ratio
  - Reduced frequency
  - Amplitude of oscillations

*Palacios, Murua, Cook. AIAA J (to appear)
UVLM against 2D strip theory*

- Strip theory Vs. UVLM
- Parabolic flapping
  \[ w(y, t) = Ay^2 \cos(\omega t) \]
- Large deformations
  - Up to 30% of semi-span

*Palacios, Murua, Cook. AIAA J (to appear)
Geometrically-nonlinear composite beams

- $3D \rightarrow 1D$ homogenization
- Large deformations and global rotations
- Small strains and local rotations
Geometrically-nonlinear composite beams

- 3D → 1D homogenization
- Large deformations and global rotations
- Small strains and local rotations

Rigid-body DoF

\[ \beta = \begin{bmatrix} v_a \\ \omega_a \end{bmatrix} \]

Structural DoF (displacement-based FE)

\[ \eta = \begin{bmatrix} R_a \\ \Psi \end{bmatrix} \approx N\bar{\eta} \]
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\[
M_{\eta}(\bar{\eta}) \begin{bmatrix} \ddot{\beta} \\ \ddot{\bar{\eta}} \end{bmatrix} + \mathbf{F}_{\text{gyr}}(\beta, \bar{\eta}, \dot{\bar{\eta}}) + \mathbf{F}_{\text{stif}}(\bar{\eta}) - \mathbf{F}_{\text{ext}}
\]

\[
\dot{\zeta} = -\frac{1}{2} \gamma(\omega_a) \zeta
\]

\[
\dot{p}_a = v_a
\]
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Flexible-beam dynamics

\[ M_\eta(\overline{\eta}) \left\{ \frac{\ddot{\beta}}{\overline{\eta}} \right\} + F_{\text{gyr}}(\beta, \overline{\eta}, \dot{\overline{\eta}}) + F_{\text{stif}}(\overline{\eta}) - F_{\text{ext}} = 0 \]

\[ \dot{\zeta} = -\frac{1}{2} \Gamma(\omega_a) \zeta \]

\[ \dot{P}_a = v_a \]
Geometrically-nonlinear composite beams

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Rigid-body DoF (displacement-based FE)

$$\beta = \begin{pmatrix} v_a \\ \omega_a \end{pmatrix}$$

Structural DoF

$$\eta = \begin{pmatrix} R_a \\ \Psi \end{pmatrix} = N\bar{\eta}$$

$$M_\eta(\bar{\eta}) \begin{bmatrix} \ddot{\beta} \\ \ddot{\eta} \end{bmatrix} + F_{gyr}(\beta, \bar{\eta}, \dot{\eta}) + F_{stiff}(\bar{\eta}) - F_{ext}$$

$$\dot{\zeta} = -\frac{1}{2} \gamma(\omega_a) \zeta$$

$$\dot{p}_a = v_a$$

Propagation of body-attached FoR
Static analysis of HALE aircraft

- Patil et al (2001) → 2D aerodynamics

**HALE model characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>16</td>
</tr>
<tr>
<td>Elastic axis (from le)</td>
<td>50 %</td>
</tr>
<tr>
<td>Center of gravity (from le)</td>
<td>50 %</td>
</tr>
<tr>
<td>Mass per unit length</td>
<td>0.75 kg/m</td>
</tr>
<tr>
<td>Torsional rigidity</td>
<td>$2 \times 10^4$ N·m²</td>
</tr>
<tr>
<td>Bending rigidity</td>
<td>$1 \times 10^4$ N·m²</td>
</tr>
</tbody>
</table>

*Murua, Palacios, Graham. AIAA Paper 2010-8226*
Wing-tail aero interference*: effect on tail lift

- Constant angle of incidence

\[ h = A_h \sin(\omega_h t) \]
\[ \alpha = \alpha_0 + A_\alpha \cos(\omega_\alpha t) \]
\[ V_\infty = 40 \text{ m/s} \]
\[ \alpha_0 = 2.5 \text{ deg} \]

\[ A_h = 0.7894 \text{ m} \]
\[ A_\alpha = 5.6 \text{ deg} \]
\[ \omega_\alpha = \omega_h = 5 \text{ rad/s} \]

*Murua, Palacios, Graham. AIAA Paper 2010-8226
ROMs based on an intrinsic formulation
Intrinsic composite beam models

- Dynamics of a bar:
  \[ m\ddot{u} - EAu'' = N \]

- Define:
  \[ F = EAu' \]
  \[ V = \dot{u} \]
  \[ m\dot{V} - F' = N \]
  \[ \frac{1}{EA} \ddot{F} - V' = 0 \]

- For general geometrically-nonlinear problems (Hodges, 2003):
  \[ m\dot{x}_1 - x'_2 - ex_2 + L_1(x_1)mx_1 + L_2(x_2)cx_2 = f_1 \]
  \[ cx_2 - x'_1 + e^T x_2 - L_1(x_1)c x_2 = 0 \]

- No displacements/rotations are needed for free vibrations or following forces. Rigid-body analogy.
Aeroelastic equations in intrinsic modal coordinates

- (Unsteady) thin-strip assumption: aero as following forces.
- Project on normal modes of linear intrinsic equations

\[ x_1(x,t) = \Phi_{1j}(x)q_{1j}(t) \]
\[ x_2(x,t) = \Phi_{2j}(x)q_{2j}(t) \]

\[ \dot{q}_{1j} - \omega_j q_{2j} + \left( \beta_{1j}^{kl} - \rho_x \mu_j^{kl} \right) q_{1k} q_{1l} + \beta_{2j}^{kl} q_{2k} q_{2l} = 0 \]
\[ \dot{q}_{2j} + \omega_j q_{1j} + \beta_{3j}^{kl} q_{1k} q_{2l} = 0 \]

- Free vibrations: nonlinear normal modes (beam as in (Pai,2007))

*Palacios, R. Journal of Sound and Vibration (to appear)
Aeroelastic equations in intrinsic modal coordinates

- Quasi-steady aerodynamics on free-free isotropic beam.

\[ \rho_\infty = 0 \]

\[ \rho_\infty = 1 \text{ kg/m}^3 \]
• Quasi-steady aerodynamics on free-free isotropic beam.

\[ \rho_\infty = 0 \]

\[ \rho_\infty = 2 \text{ kg/m}^3 \]
Final remarks

- Multidisciplinary analysis of low-speed flexible vehicles

- Physics-based, low-fidelity

- Key aspects of aero and structural models have been identified (numerical efficiency, couplings, 3-D effects)

- Intrinsic equations for ROM

- Next:
  - Flexible aircraft FCS development
  - Integration of structural homogenisation → MDO