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Low-order Aeroelastic Modelling of Highly-Deformable Wings

ECERTA Workshop
Liverpool, 13-14 Sept 2010

Rafael Palacios, Joseba Murua, Robbie Cook

http://www.imperial.ac.uk/aeroelastics

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Overview

- The context → Building ever more efficient aircraft (larger, lighter)
- Multidisciplinary analysis:
  - Structures
  - Aerodynamics
  - Flight dynamics
  - Controls
  - Failure analysis, power management...
- Non-linear flight dynamics of flexible aircraft
- Reduced-order models
- Conclusions and future directions

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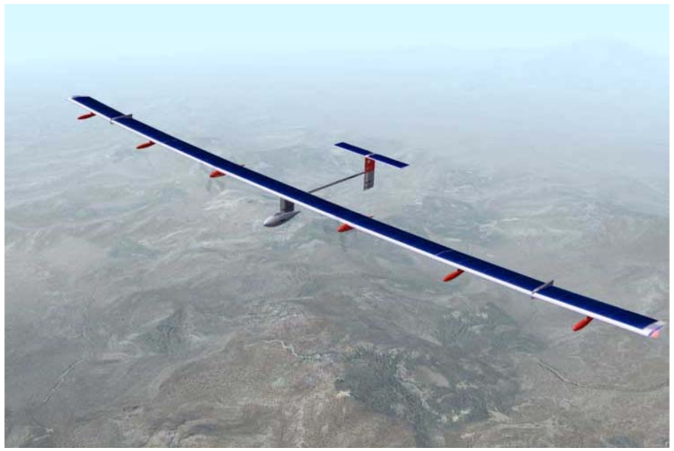
The challenge of very high efficiency

QinetiQ **Zephyr**

Lockheed Martin **MPLE UAS**



Solar Impulse

ETA aircraft (Flugtechnik & Leichtbau)

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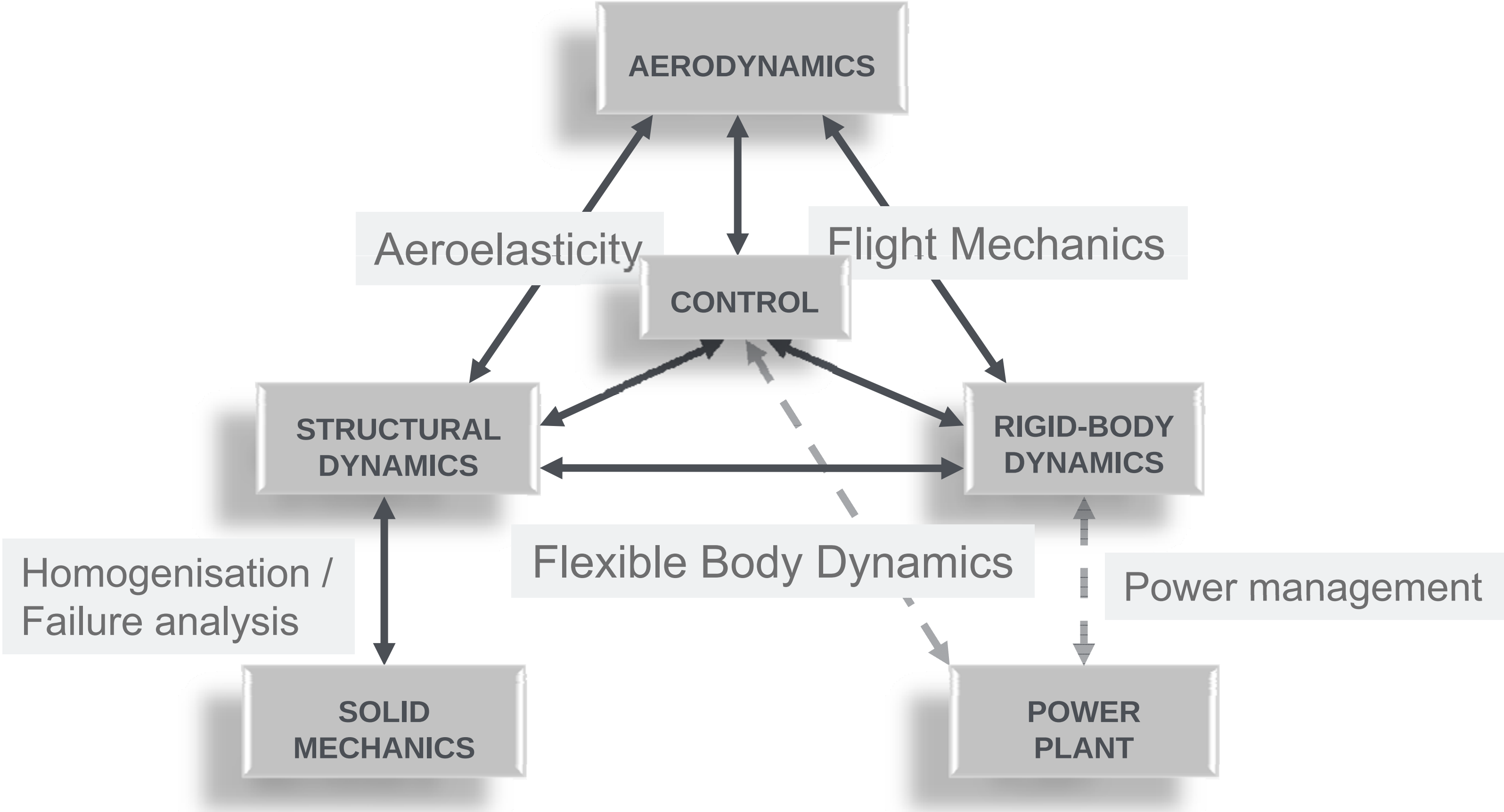
Multidisciplinary approach for full aircraft dynamics

- A systems integration problem...



Helios mishap report*

"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."

*Noll et al (2004). "Investigation of the Helios Prototype Aircraft Mishap." NASA TR 64317

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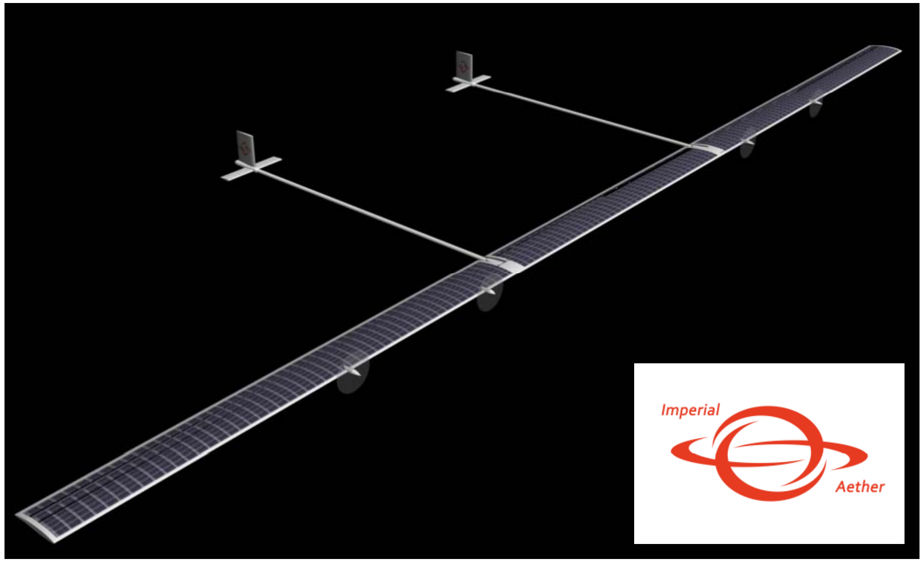
Research objectives

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

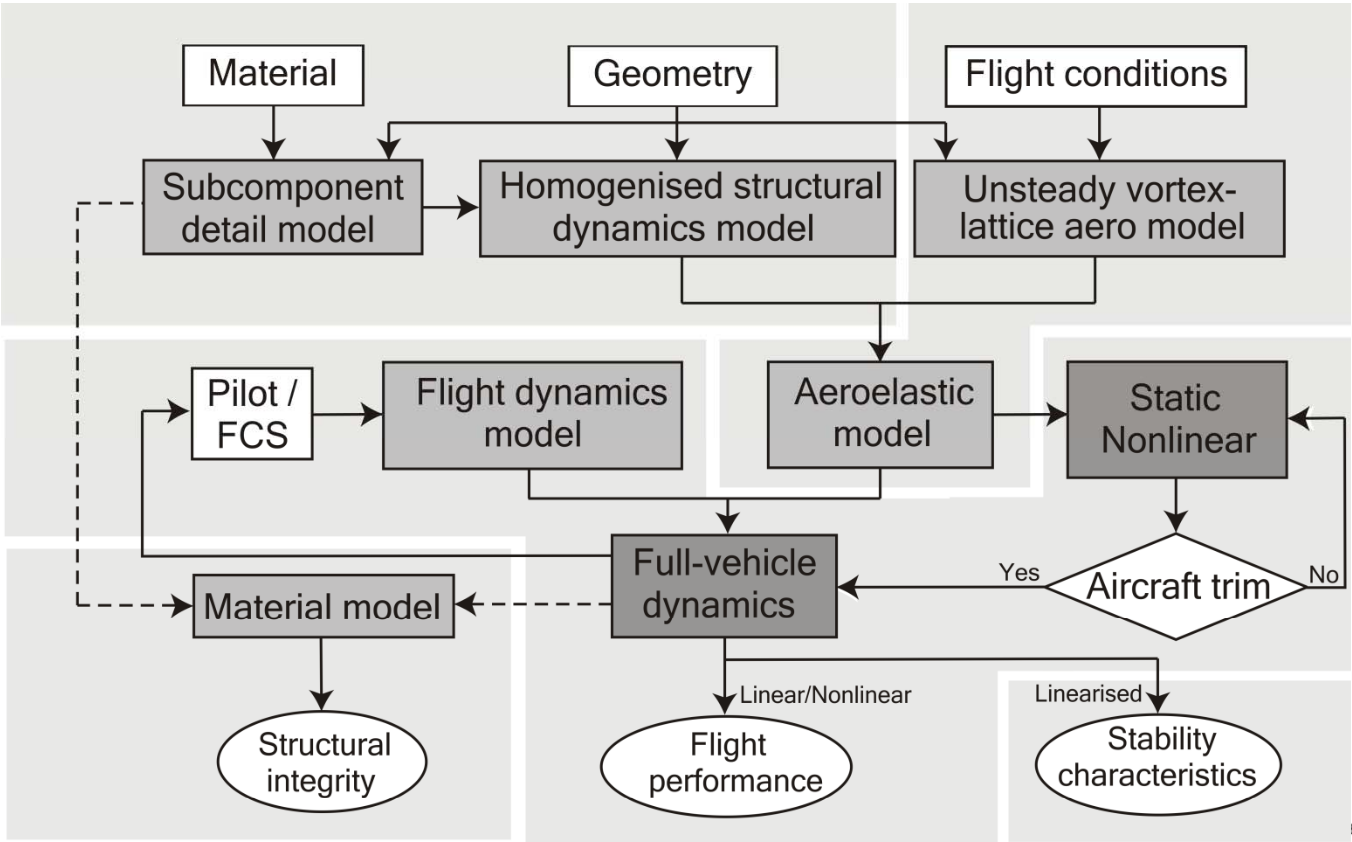
- **Predicting** performance and flight qualities
  - o Multiscale approach for full aircraft analysis
  - o Evaluation of non-conventional configurations
  - o Virtual aircraft test bed for technology evaluation

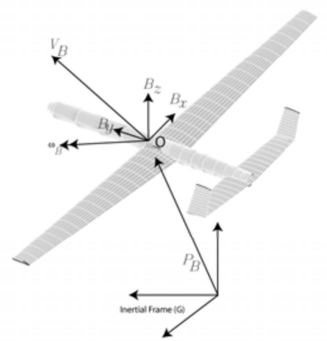
- **Exploring** the design space
  - o Reduced-order models
  - o FCS with (geom-nonlinear) structural dynamics

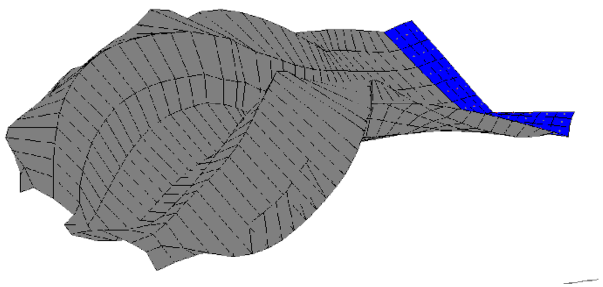


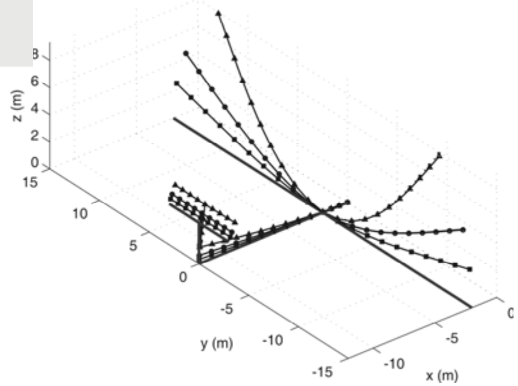
2009 Imperial Aero 3rd–year Group Design Project

Flexible Aircraft Flight Dynamics Simulation

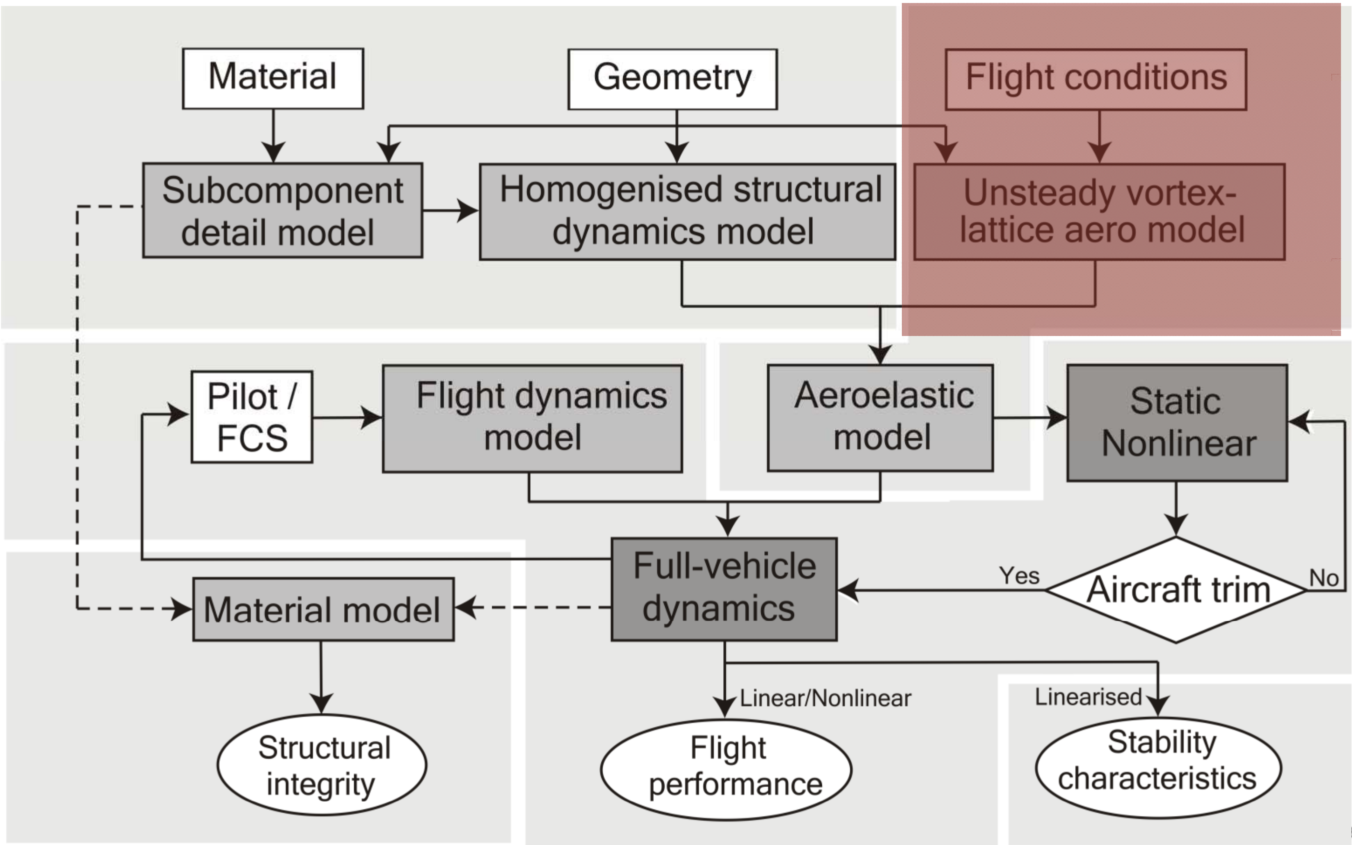


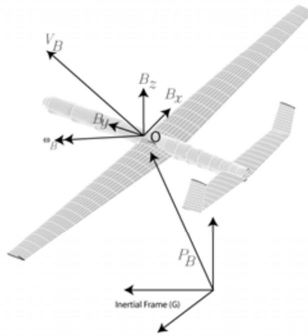


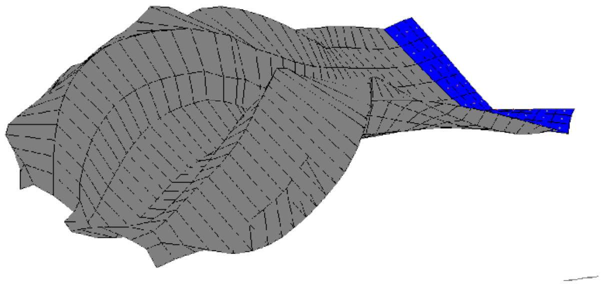


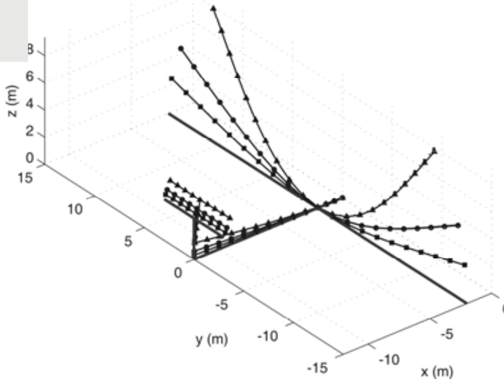


Unsteady Aerodynamics









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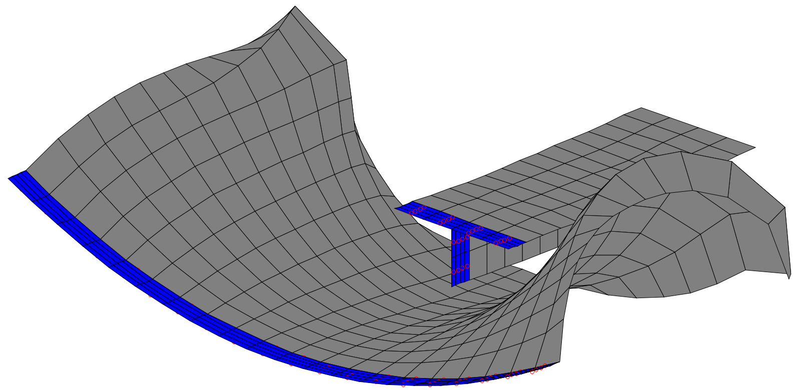
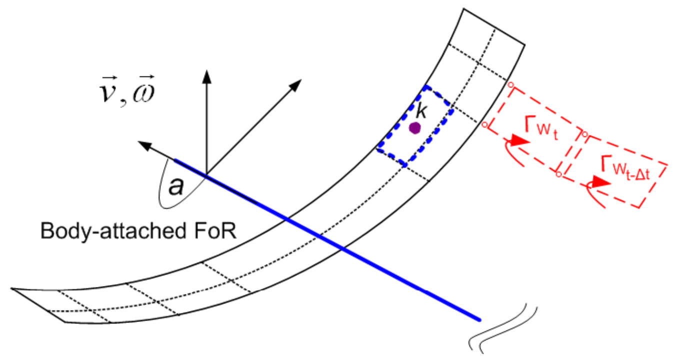
Unsteady Vortex Lattice Method (UVLM)

- Vortex-ring discretization, as Falkner (1946), Katz & Plotkin (2001)
- Potential flow, thin airfoil → Low speed flight, attached flow
- 3-D, unsteady, free-wake, interference, large (but slow) wing displacements





UVLM: discrete-time formulation

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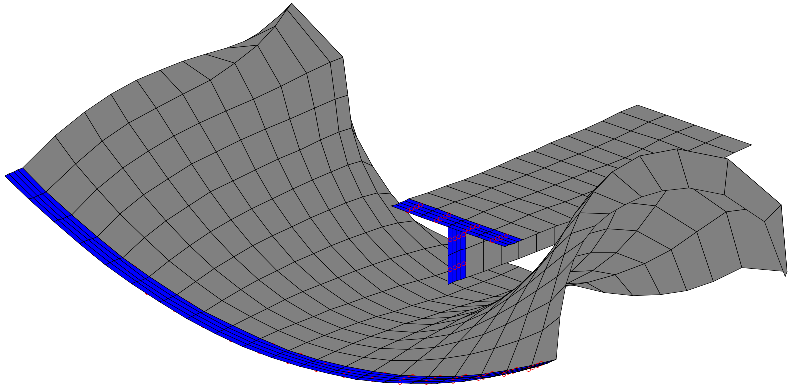
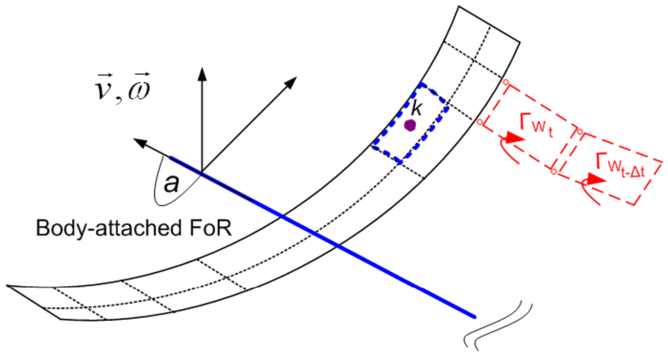


$$\begin{Bmatrix} \Gamma_b \\ \Gamma_w \\ X_w \end{Bmatrix}^{n+1} = \begin{bmatrix} A & A & 0 \\ B & B^* & 0 \\ C & C^* & D \end{bmatrix} \begin{Bmatrix} \Gamma_b \\ \Gamma_w \\ X_w \end{Bmatrix}^{n} + \begin{Bmatrix} E \\ 0 \\ 0 \end{Bmatrix} w^{n+1}$$



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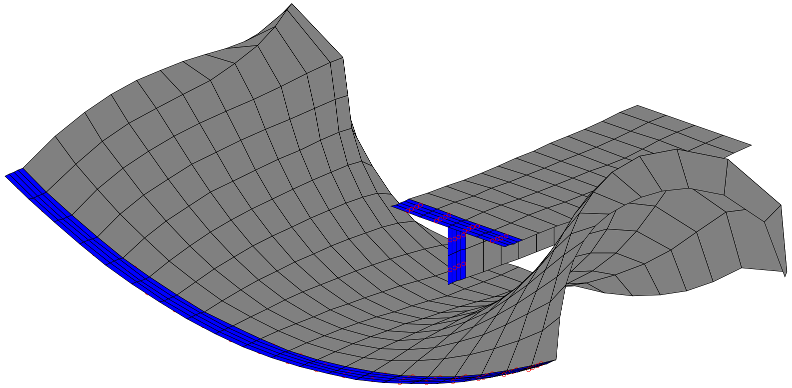
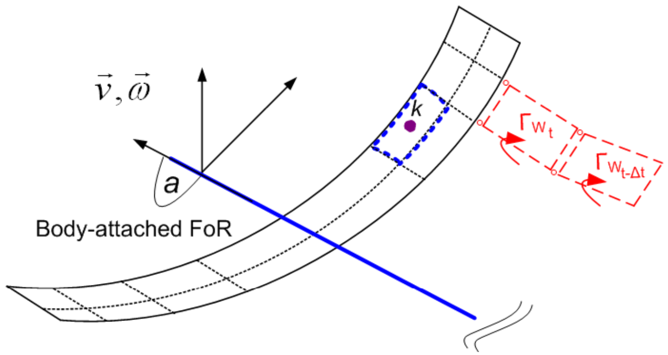


Non-penetration boundary condition

$$\begin{Bmatrix} \Gamma_b \\ \Gamma_w \\ X_w \end{Bmatrix}^{n+1} = \begin{bmatrix} A & A & 0 \\ B & B^* & 0 \\ C & C^* & D \end{bmatrix} \begin{Bmatrix} \Gamma_b \\ \Gamma_w \\ X_w \end{Bmatrix}^{n} + \begin{Bmatrix} E \\ 0 \\ 0 \end{Bmatrix} w^{n+1}$$



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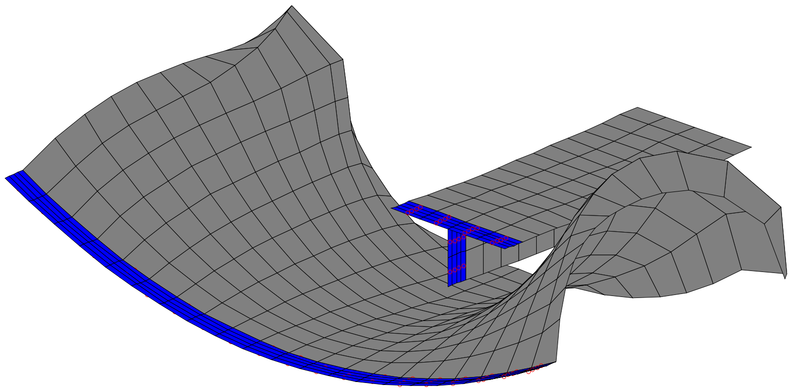

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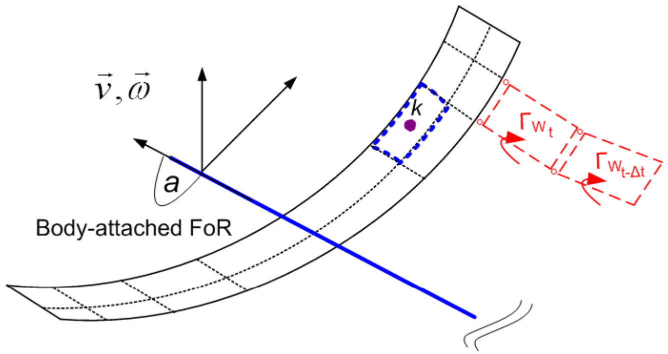
Free-wake: convection, roll up, stretching



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UVLM: aerodynamic loads from vorticity distribution

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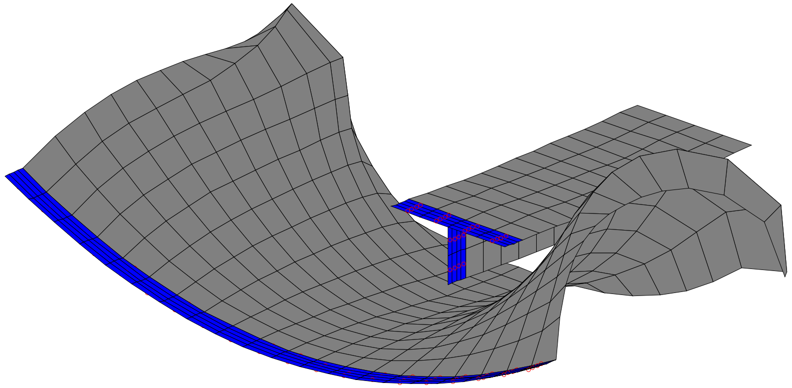

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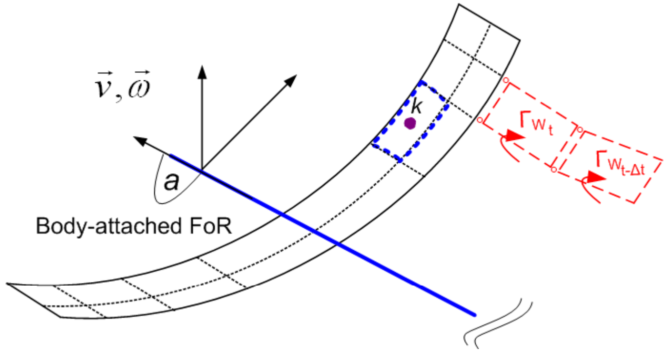
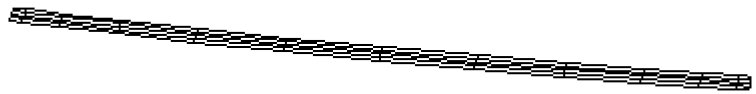
Unsteady Bernoulli equation

$$\Delta p^{n+1} = f\left(\Gamma_b^n, \Gamma_b^{n+1}, X_b^{n+1}, w^{n+1}\right)$$



3-D effects in unsteady aerodynamics*

- UVLM vs. thin strip aero



- Prescribed Kinematics

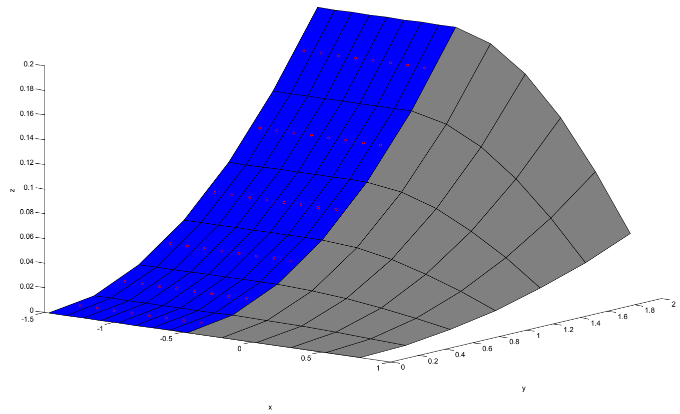
$$w(y,t) = Ay^2 \cos\left(\omega t\right)$$

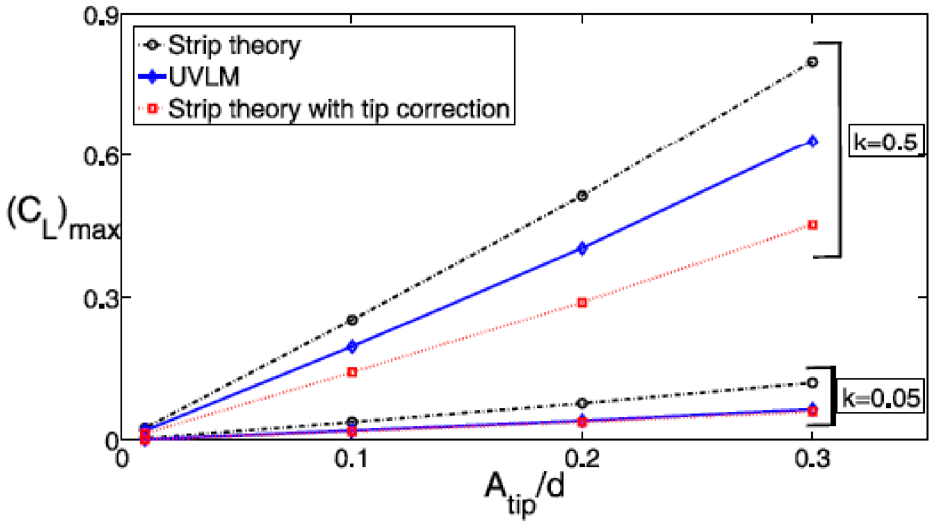
- Investigate effect of
  - o Aspect ratio
  - o Reduced frequency
  - o Amplitude of oscillations

*Palacios, Murua, Cook. AIAA J (to appear)

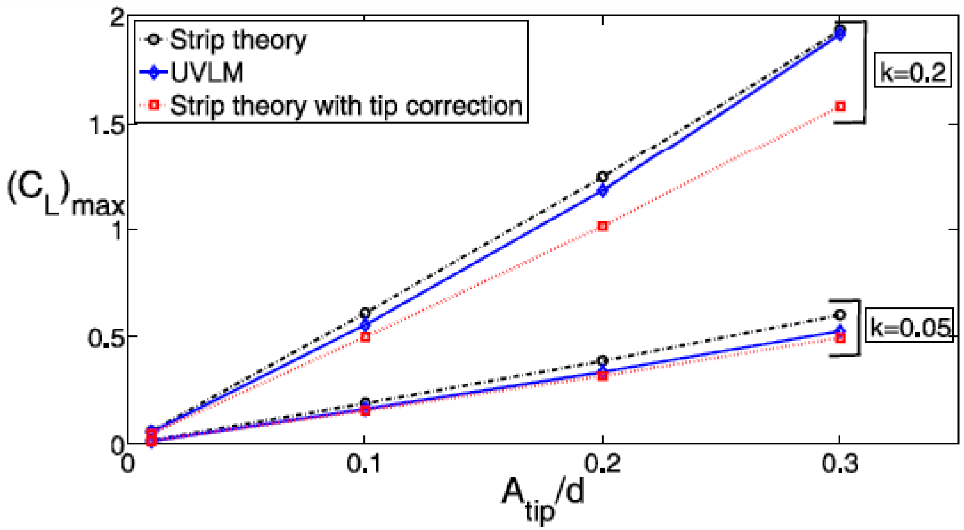
UVLM against 2D strip theory*

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





Low aspect ratio (AR=2)



High aspect ratio (AR=10)

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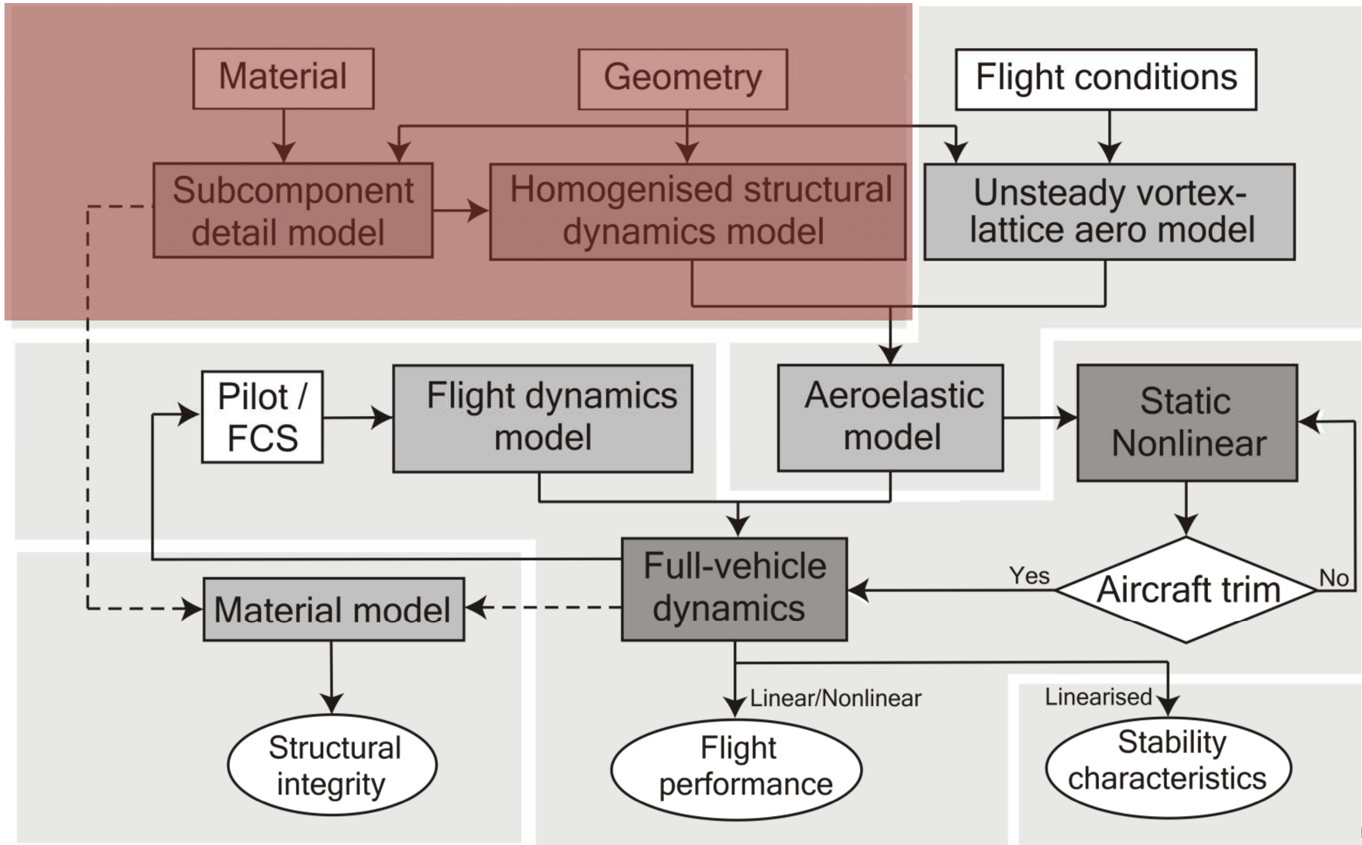
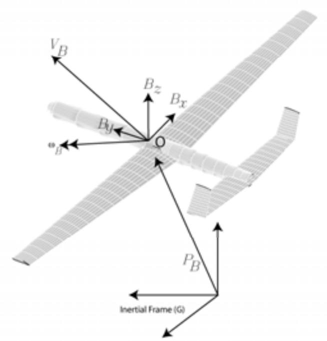
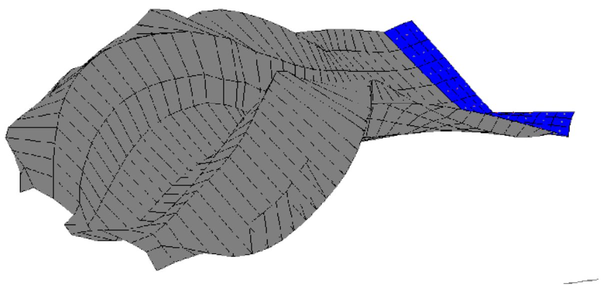
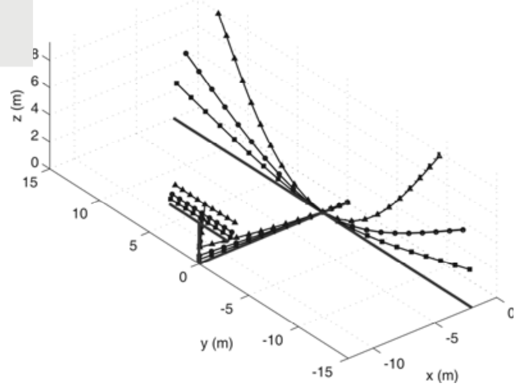
Structural Dynamics



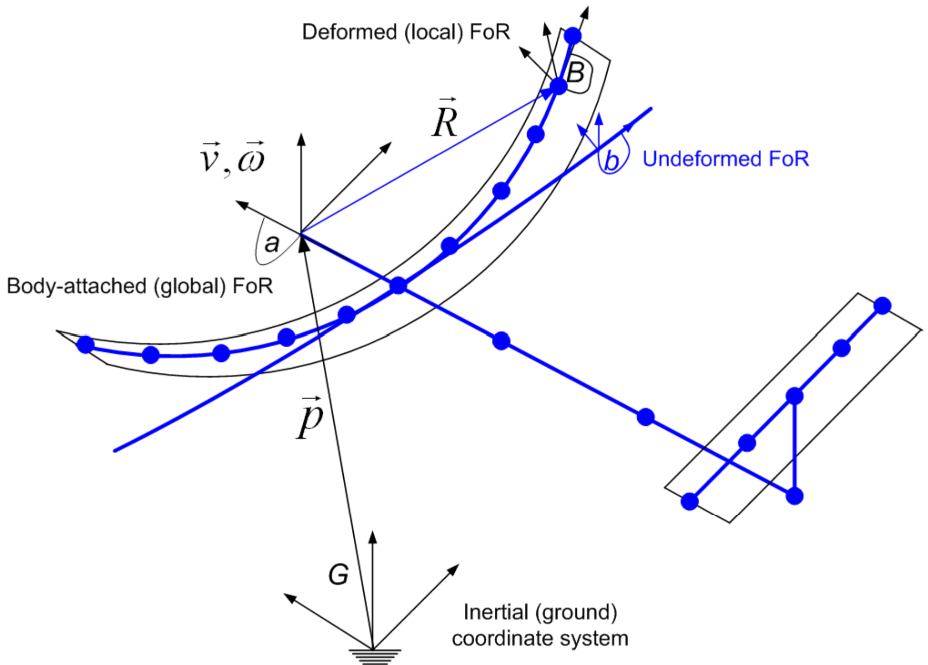






Geometrically-nonlinear composite beams

- Simo & Vu-Quoc (1986), Cardona & Geradin (1988)
- 3D → 1D homogenization
- Large deformations and global rotations
- Small strains and local rotations



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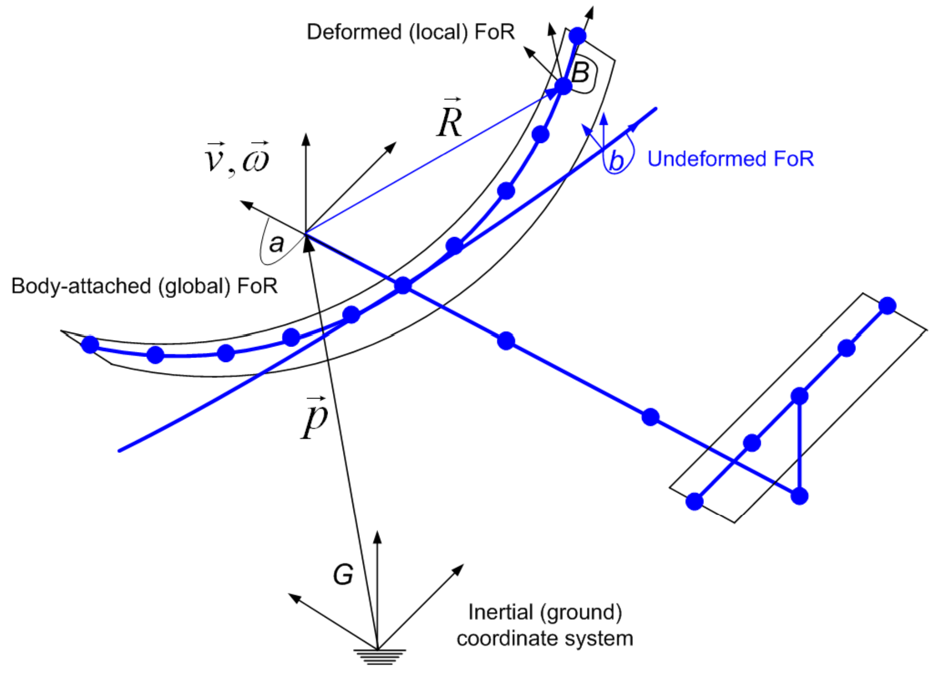
Rigid-body DoF

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

Structural DoF (displacement-based FE)

$$\eta = \begin{Bmatrix} R_a \\ \Psi \end{Bmatrix} \approx N\overline{\eta}$$



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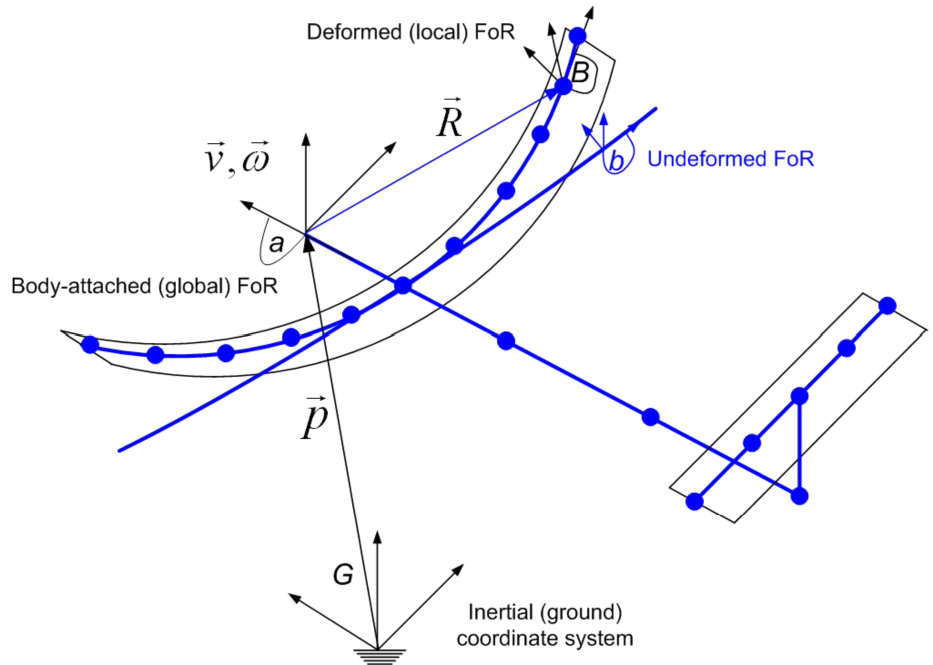
$$\dot{\zeta} = -\frac{1}{2}\Upsilon(\omega_a)\zeta$$

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



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Flexible-beam dynamics

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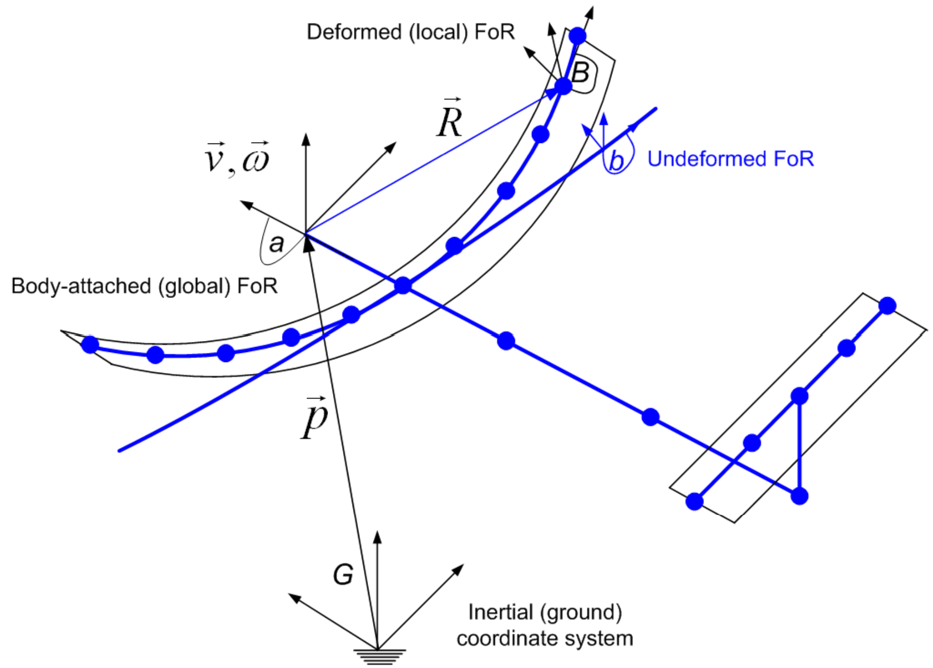

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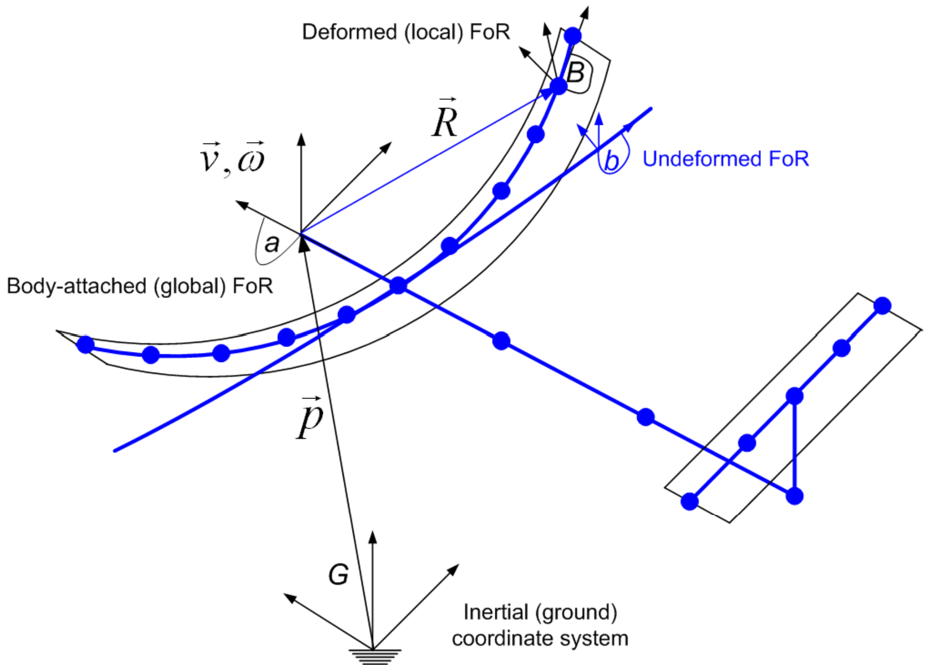
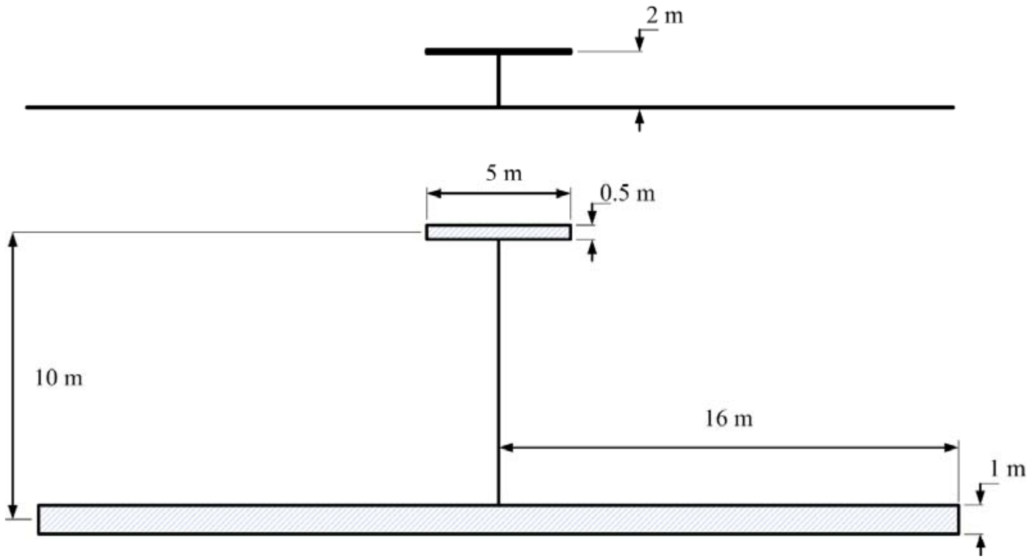
Propagation of body-attached FoR

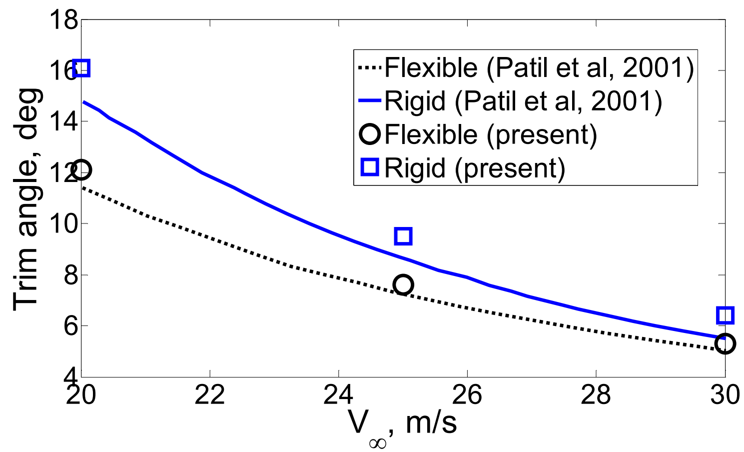


Static analysis of HALE aircraft*

- Patil et al (2001) → 2D aerodynamics



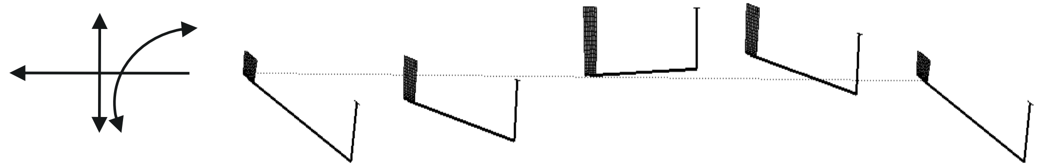
HALE model characteristics	
Aspect ratio	16
Elastic axis (from le)	50 %
Center of gravity (from le)	50 %
Mass per unit length	0.75 kg/m
Torsional rigidity	2×10^4 N·m^2
Bending rigidity	1×10^4 N·m^2



*Murua, Palacios, Graham. AIAA Paper 2010-8226

Wing-tail aero interference*: effect on tail lift

- Constant angle of incidence



$$h = A_h \sin(\omega_h t)$$

$$\alpha = \alpha_0 + A_\alpha \cos(\omega_\alpha t)$$

$$V_\infty = 40 \text{ m/s}$$

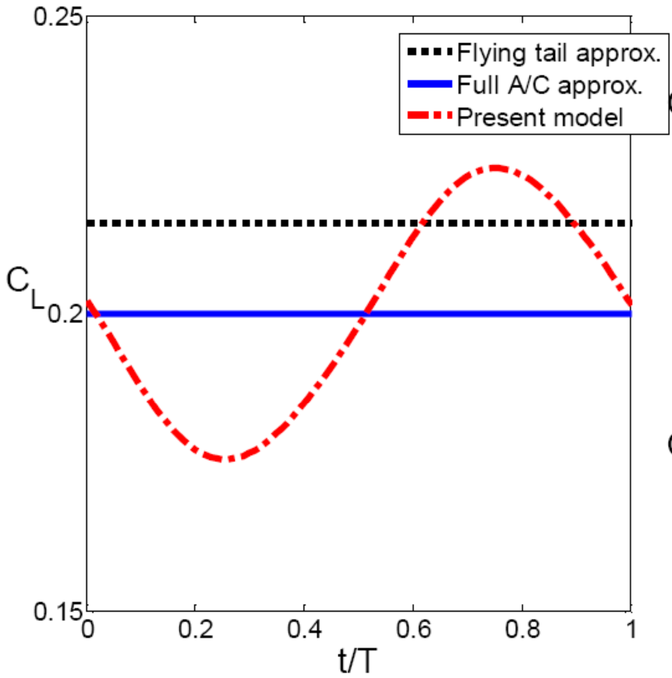
$$\alpha_0 = 2.5 \text{ deg}$$

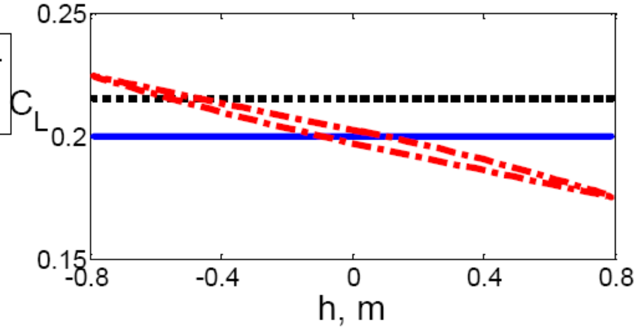
$$A_h = 0.7894 \text{ m}$$

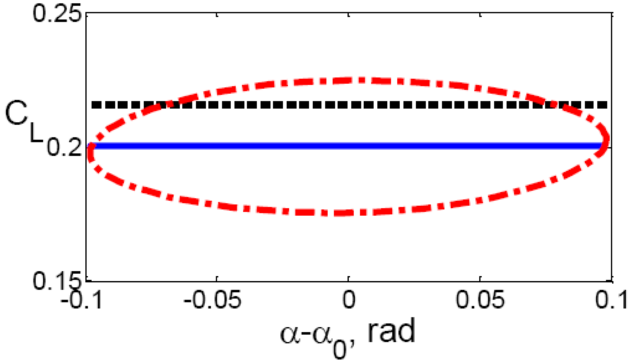
$$A_\alpha = 5.6 \text{ deg}$$

$$\omega_\alpha = \omega_h = 5 \text{ rad/s}$$

Constant incidence







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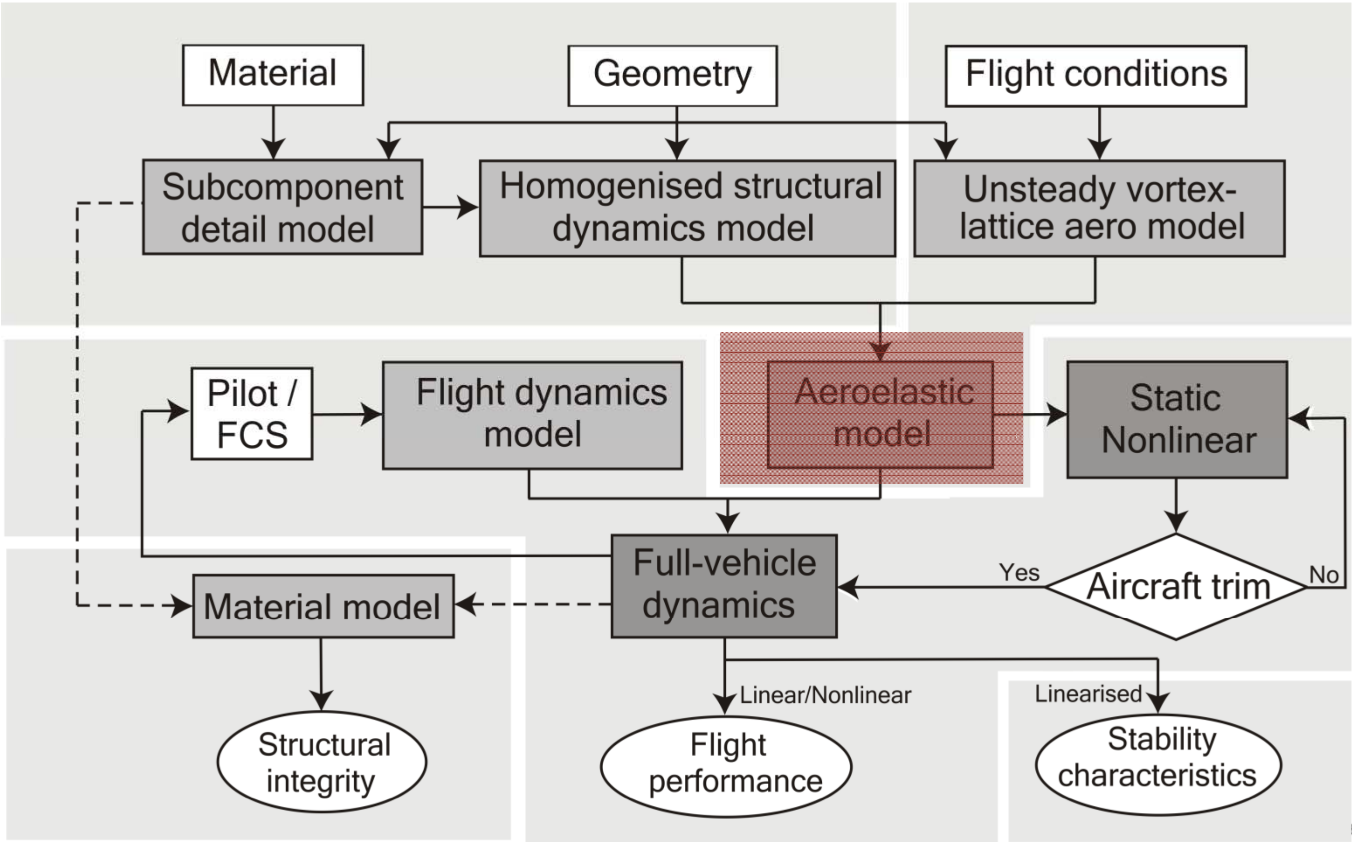
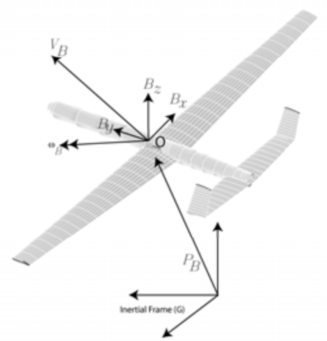
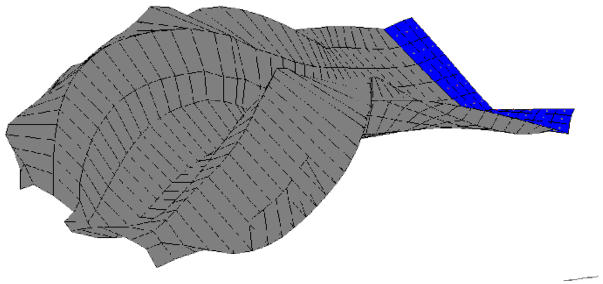
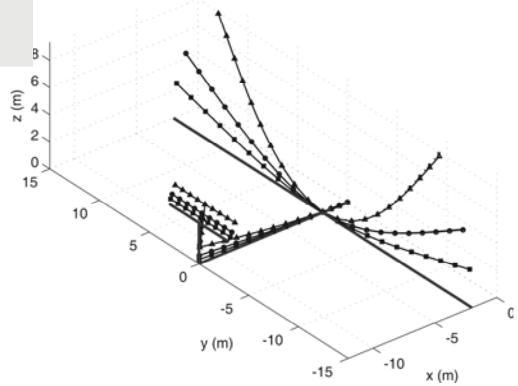
ROMs based on an intrinsic formulation









Intrinsic composite beam models

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

- Define: $$F = EAu' \qquad V = \dot{u}$$ $$\Rightarrow \quad m\dot{V} - F' = N, \qquad \frac{1}{EA}\dot{F} - V' = 0$$

- For general geometrically-nonlinear problems (Hodges, 2003):

$$\mathbf{m}\dot{\mathbf{x}}_\mathbf{1} - \mathbf{x}_2' - \mathbf{e}\mathbf{x}_2 + \mathrm{L}_1(\mathbf{x}_1)\mathbf{m}\mathbf{x}_1 + \mathrm{L}_2(\mathbf{x}_2)\mathbf{c}\mathbf{x}_2 = \mathbf{f}_\mathbf{1}$$
$$\mathbf{c}\dot{\mathbf{x}}_2 - \mathbf{x}_1' + \mathbf{e}^T\mathbf{x}_2 - \mathrm{L}_1(\mathbf{x}_1)\mathbf{c}\mathbf{x}_2 = \mathbf{0}$$

- No displacements/rotations are needed for **free vibrations** or **following forces**. Rigid-body analogy.

Aeroelastic equations in intrinsic modal coordinates

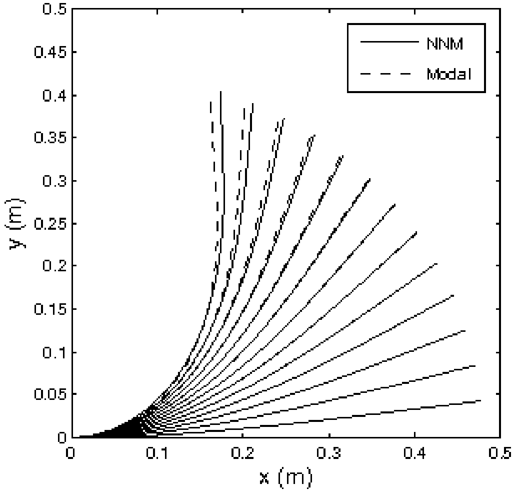
- (Unsteady) thin-strip assumption: aero as following forces.
- Project on normal modes of linear intrinsic equations

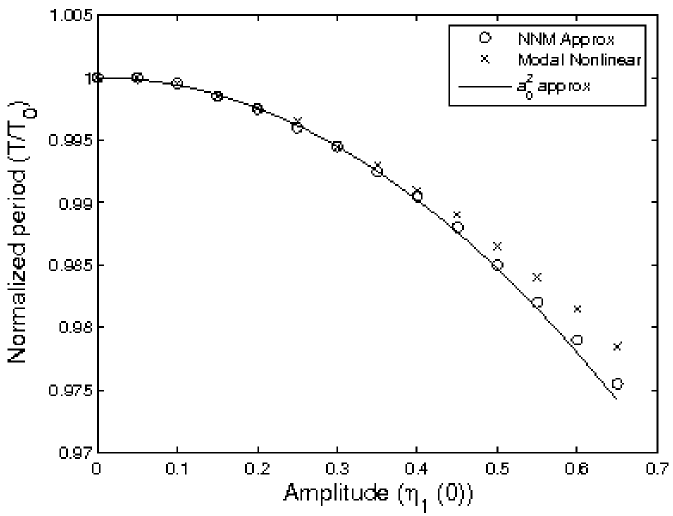
$$\mathbf{x}_1(x,t) = \Phi_{1j}(x) q_{1j}(t)$$
$$\mathbf{x}_2(x,t) = \Phi_{2j}(x) q_{2j}(t)$$

$$\Rightarrow$$

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

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



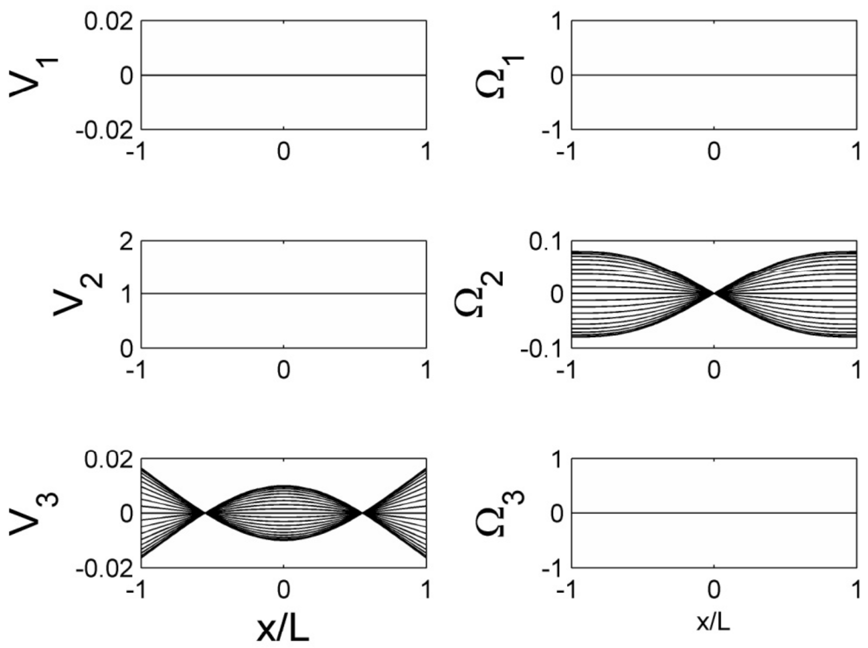


*Palacios, R. Journal of Sound and Vibration (to appear)

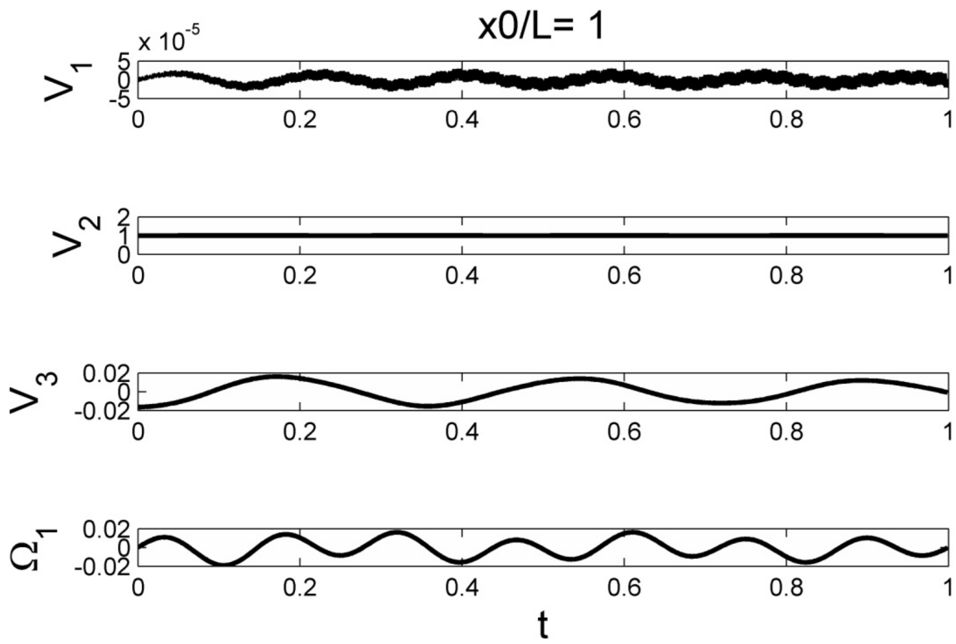
Aeroelastic equations in intrinsic modal coordinates

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

$\rho_\infty = 0$



$\rho_\infty = 1\ kg/m^3$



Aeroelastic equations in intrinsic modal coordinates

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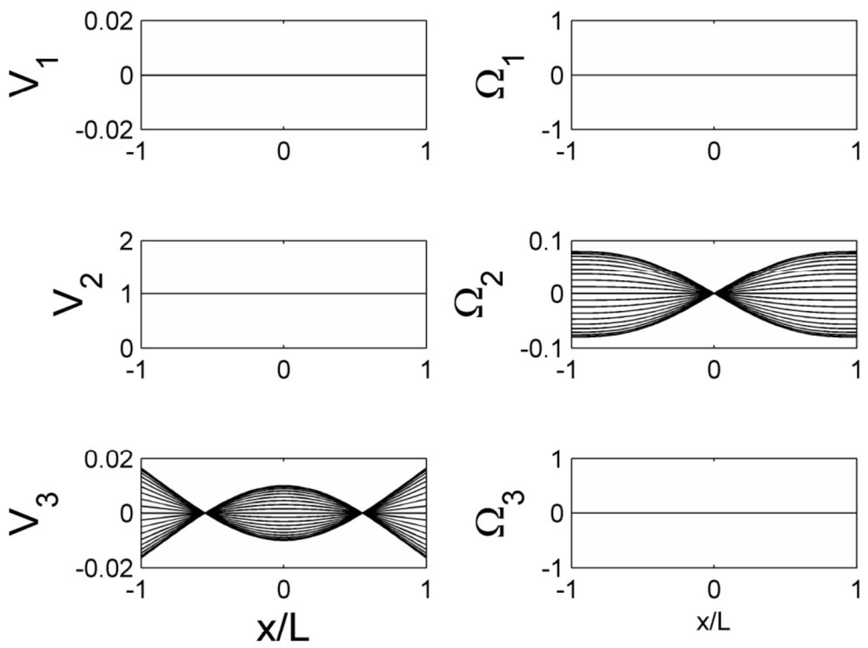
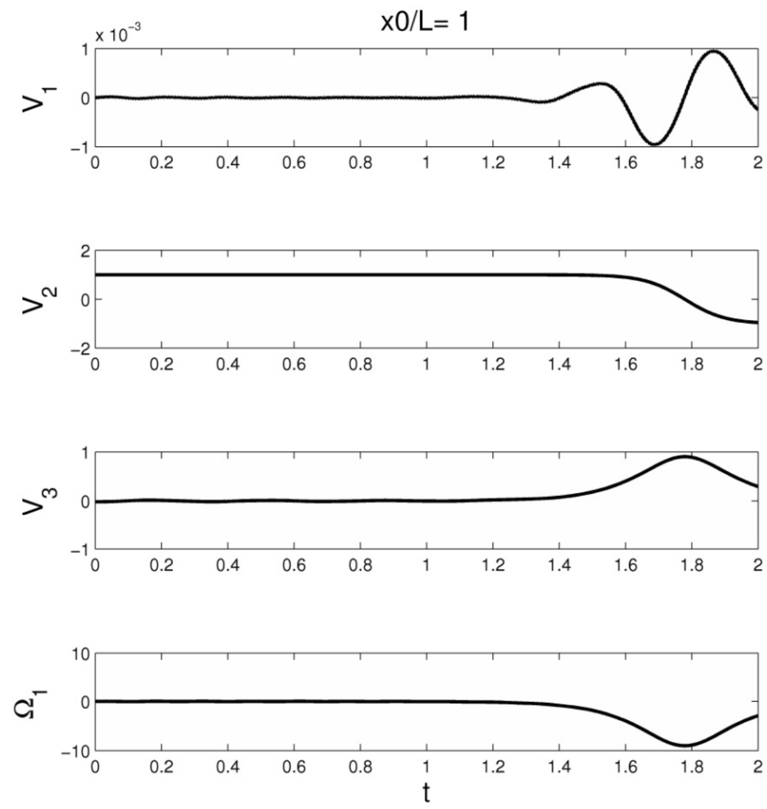


$\rho_\infty = 2\ kg/m^3$



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