Imperial College London

Load Control in Highly-Deforming Aeroelastic Systems

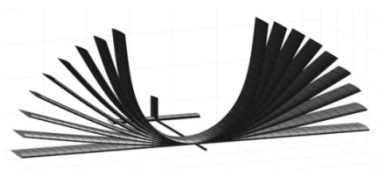
Rafael Palacios
Department of Aeronautics

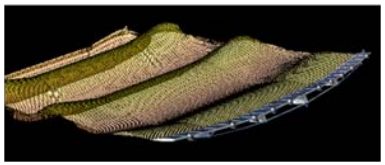
Seminar at Vibration UTC, MED
30 April 2014

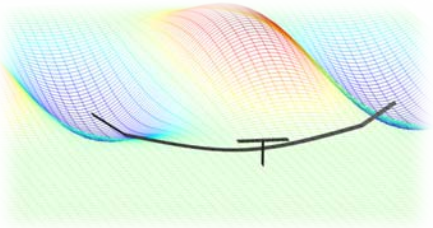
http://www.imperial.ac.uk/aeroelastics

Imperial College London

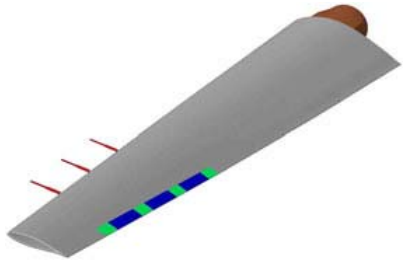
Load Control and Aeroelastics: Research Topics

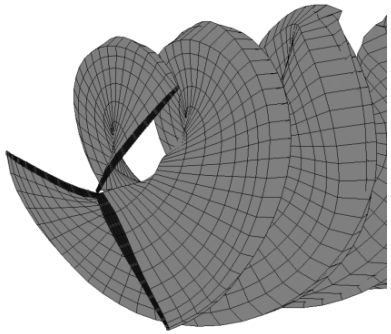




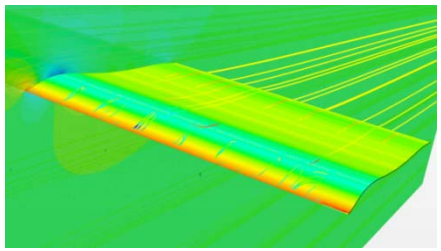


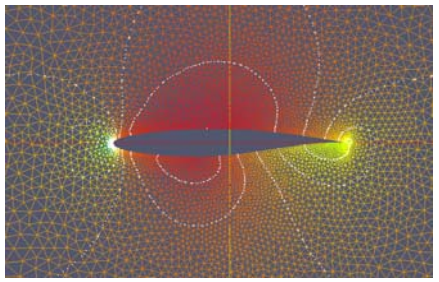
Dynamics & control of flexible aircraft





Load control in large wind turbines





Computational methods for FSI

EPSRC
Engineering and Physical Sciences Research Council

CENER

EPSRC
Engineering and Physical Sciences Research Council

EUROPEAN OFFICE OF AEROSPACE R&D

Load Control - Overview

- **Motivation:** ever more efficient airframes → perpetual flight
- **Approach:** A framework for Simulation of High-Aspect Ratio Planes
  - o Aeroelasticity with large-displacements
  - o Coupling with flight dynamics
- **Model reduction and control**
- **Examples:**
  - o Dynamic stability of very flexible aircraft
  - o Gust alleviation strategies – wake encounter
  - o On-going work

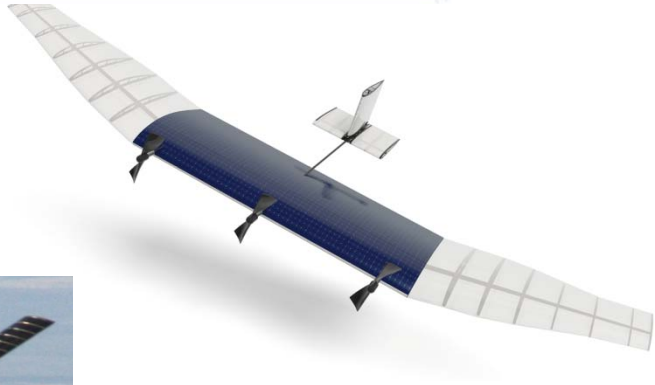
Quick Quiz

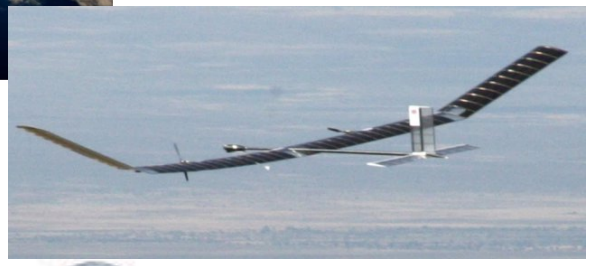
Q: What do this companies have in common?

A: They all announced a solar-powered aircraft project in April 2014

Google

facebook





AIRBUS

Imperial College London

The challenge of very high efficiency

Extreme efficiency: Solar-powered planes for “perpetual flight”

Solar Impulse 2

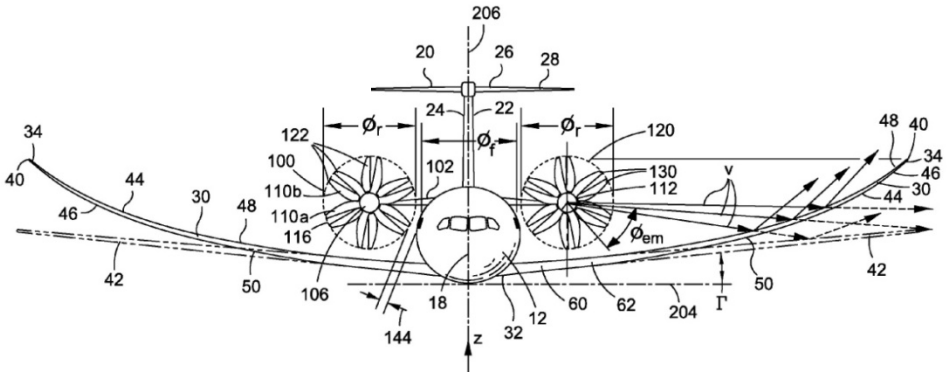
see movie

QinetiQ Zephyr 7

- Span: 22.5 m
- Weight: 53 kg
- Flight altitude: 60,000 ft
- Payload: 2.5 kg
- Power: Solar panels
  Li-S batteries

Large (and flexible) wings on transport aircraft

- Who is not interested in higher efficiency?



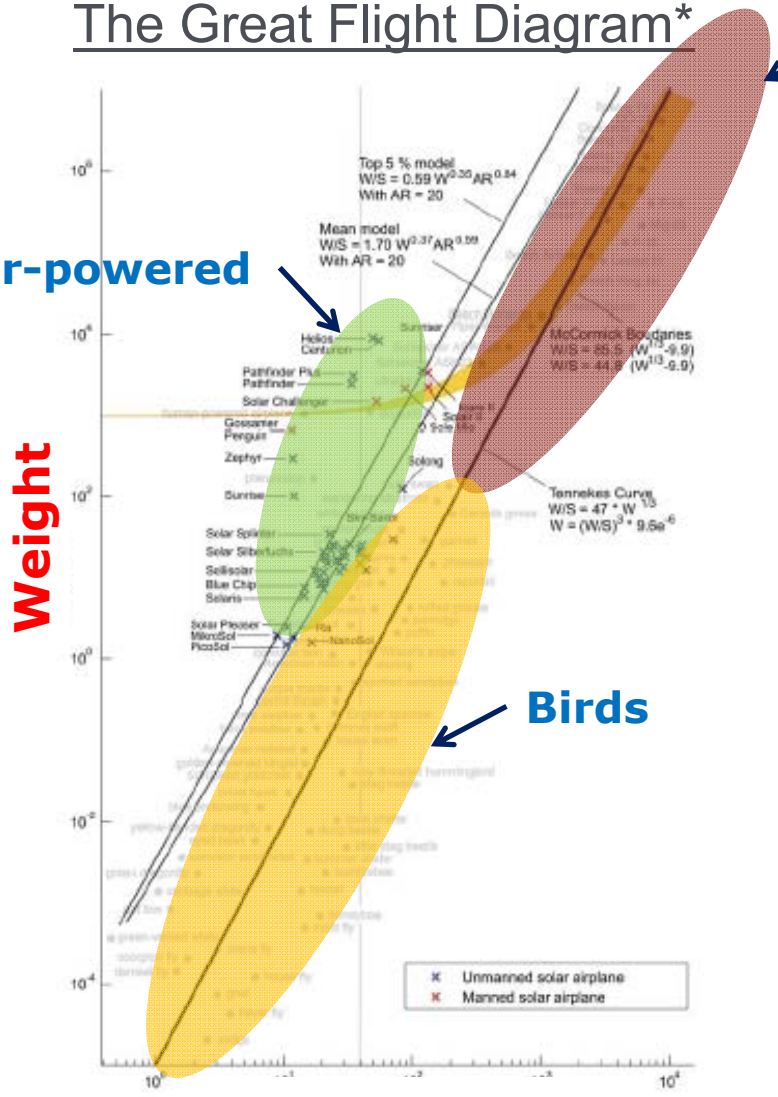
[source:USPTO]

B787 (www.aviationweek.com

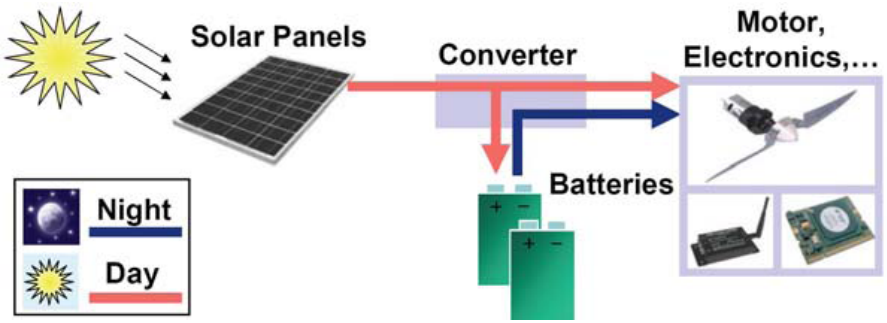
NASA **X-56A**

The challenge of very high efficiency

The Great Flight Diagram*

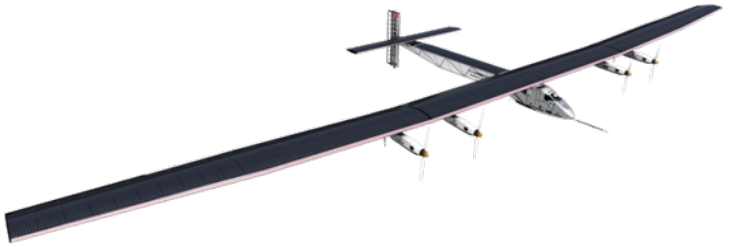


Power management:



*Noth (2006). **Design of Solar Powered Airplanes for Continuous Flight**, PhD thesis, ETH

Modelling of (very) flexible aircraft dynamics

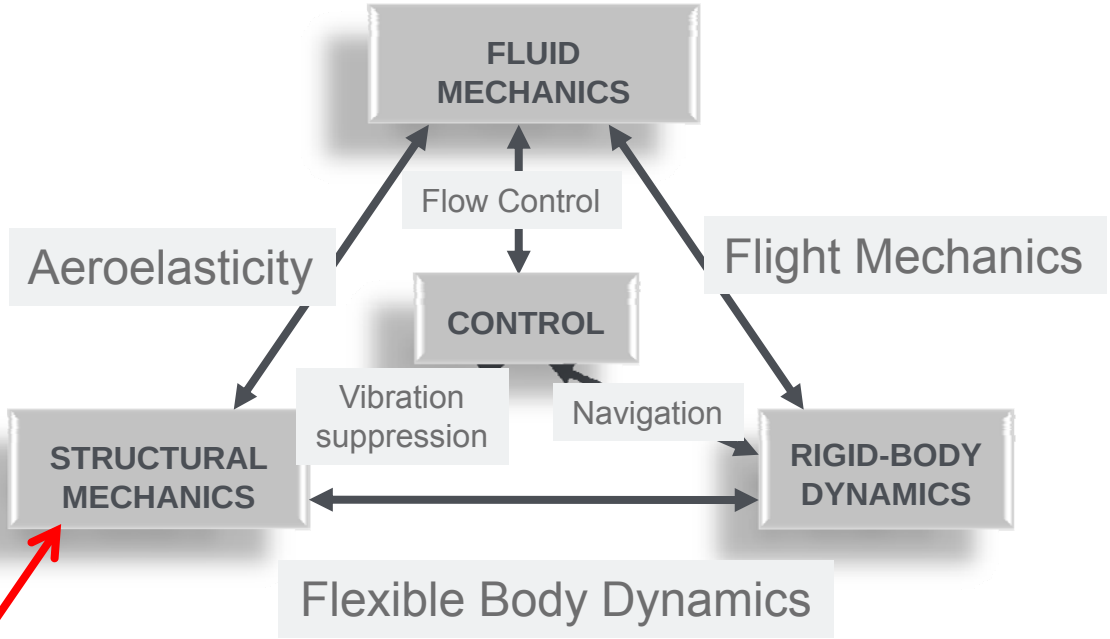


- Some major modelling challenges:
  1. Design for jig shape
  2. Validity of linear methods even more restricted in flight envelope (e.g., gust loads)
  3. **Blurred boundaries between aeroelasticity, flight dynamics, and control**

- Our objective:

"Apparent stiffness" by means of dynamic load control systems

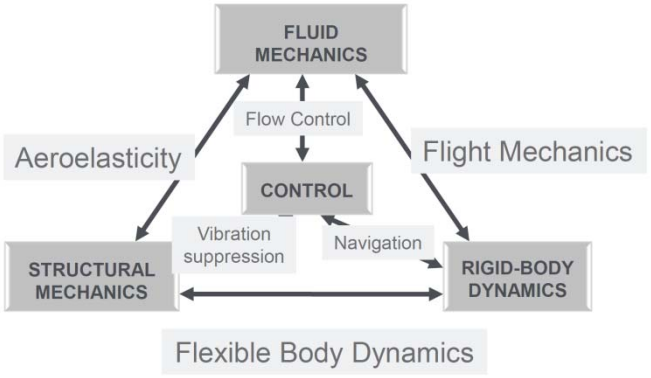
Modelling of (very) flexible aircraft dynamics



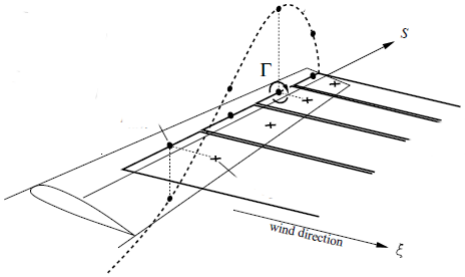
...and this is geometrically nonlinear

Modelling of (very) flexible aircraft dynamics

von Flotow (1989): *Daedalus*
- Linear beams
- Unsteady thin aerofoil
- No controls



Drela (1999): *ASWing*
- Nonlinear beams
- Unsteady lifting line
- PID control



Patil (1999) & Cesnik (2002)
- Nonlinear composite beams
- Unsteady thin aerofoil
- LQG control

(Patil & Hodges, 2006)

Wang (2010)
- Nonlinear beams
- Unstedy Vortex Lattice
- No controls

Overview

- **Motivation:** ever more efficient airframes → perpetual flight

- **Approach:** A framework for Simulation of High-Aspect Ratio Planes
  - o Aeroelasticity with large-displacements
  - o Coupling with flight dynamics

- **Model reduction and control**

- **Examples:**
  - o Dynamic stability of very flexible aircraft
  - o Gust alleviation strategies – wake encounter

  - o On-going work

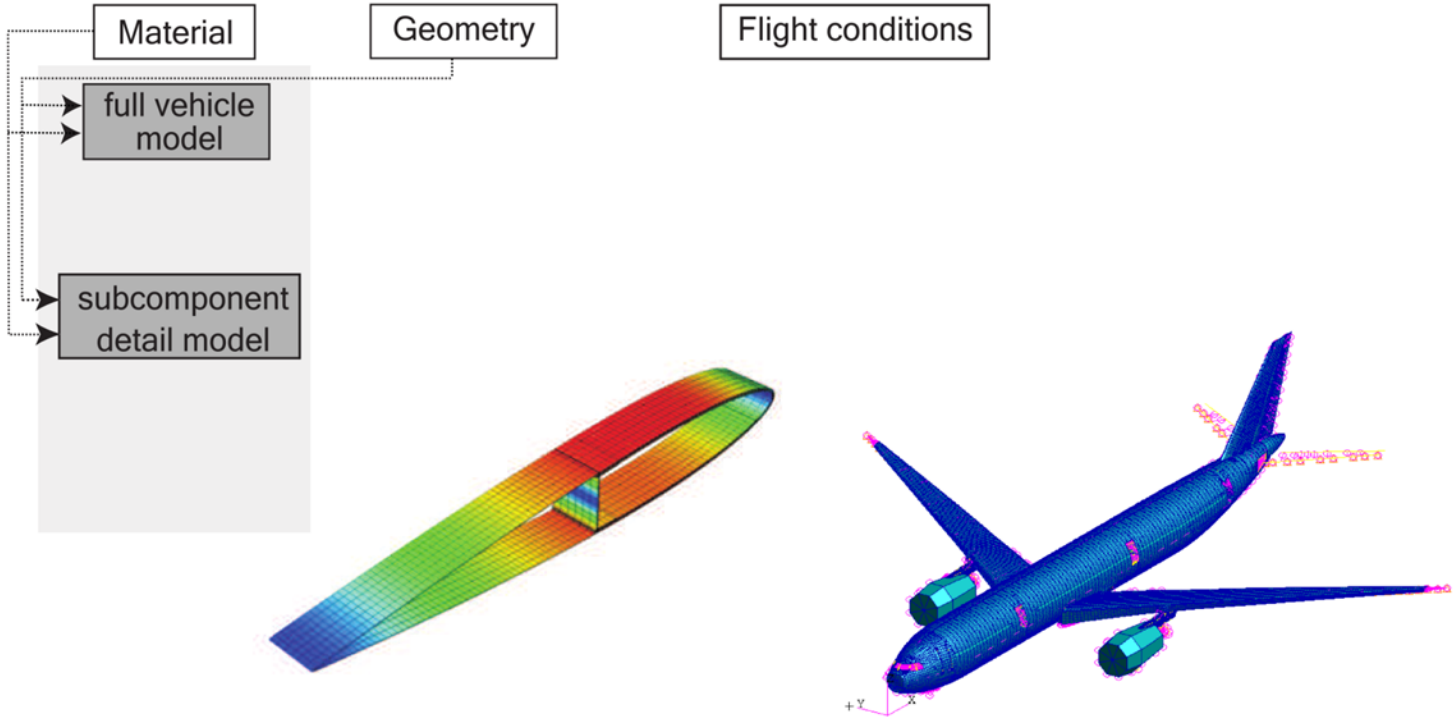
Flexible Aircraft Dynamics Simulation (SHARP)

Material

Geometry

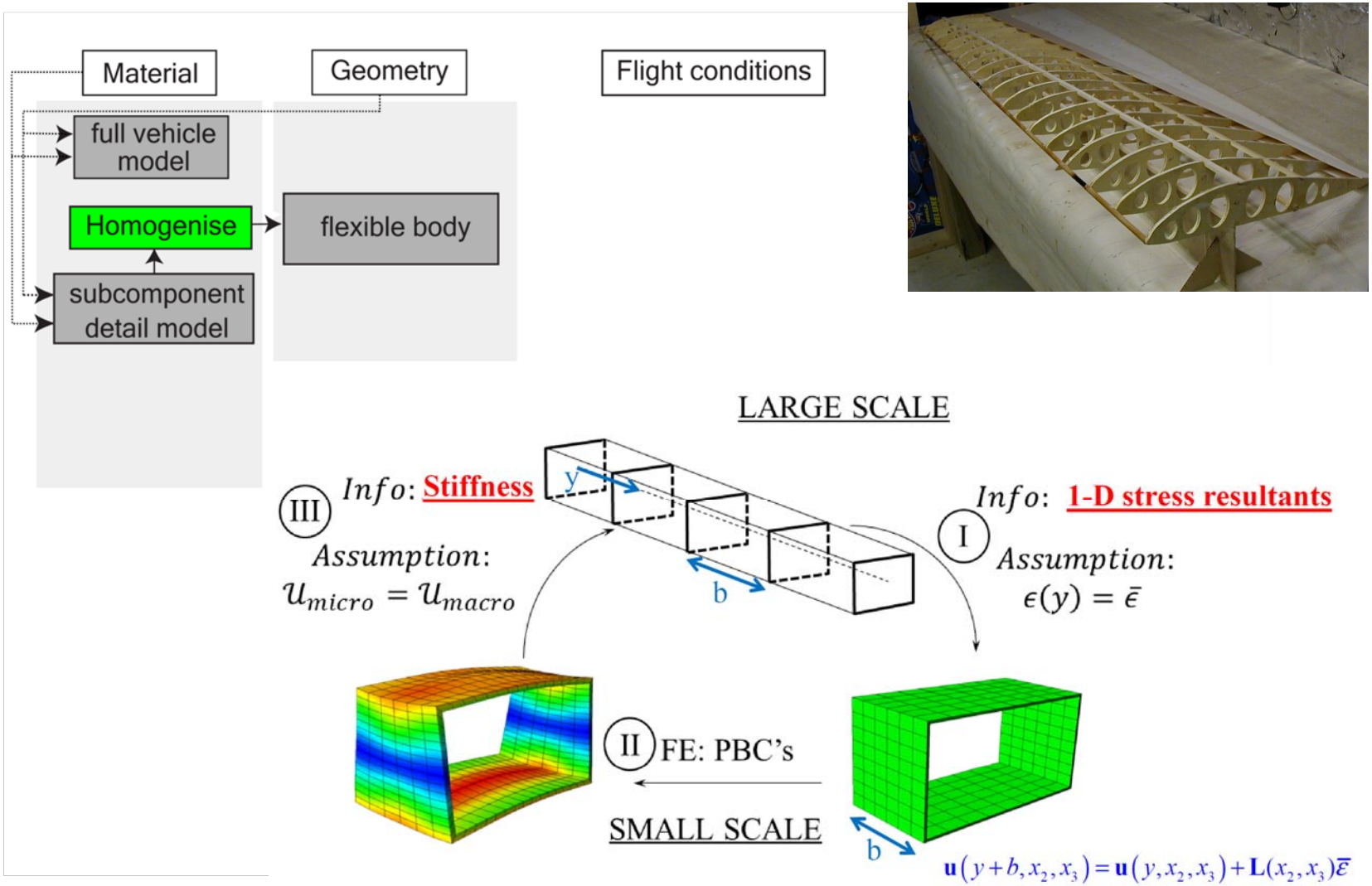
Flight conditions

SHARP: Structural Dynamics



Imperial College London

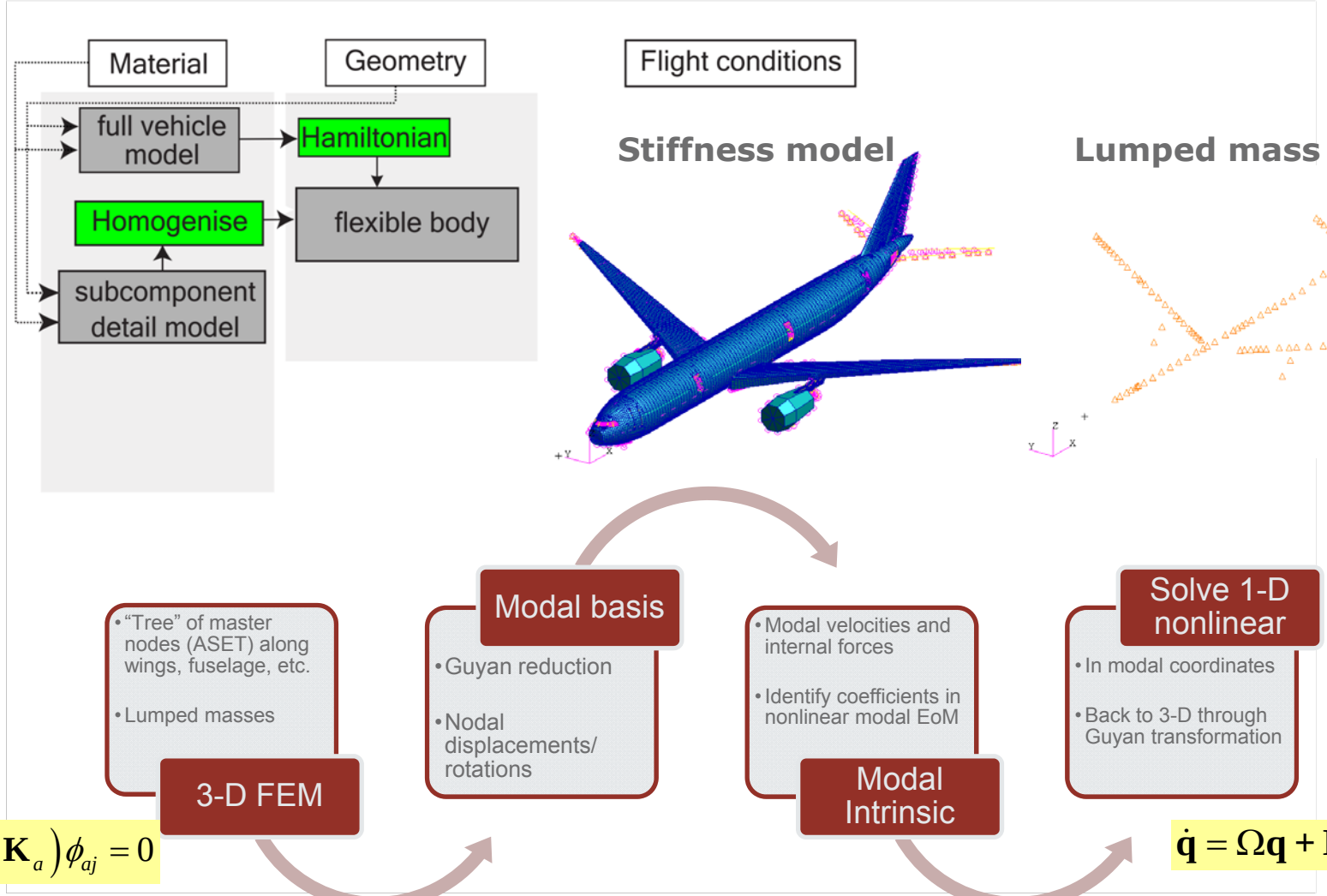
SHARP.Cells: Homogenisation of periodic structures*



*Dizy *et al.* **Homogenization of slender periodic composite structures**, IJSS 50 (2013)

Imperial College London

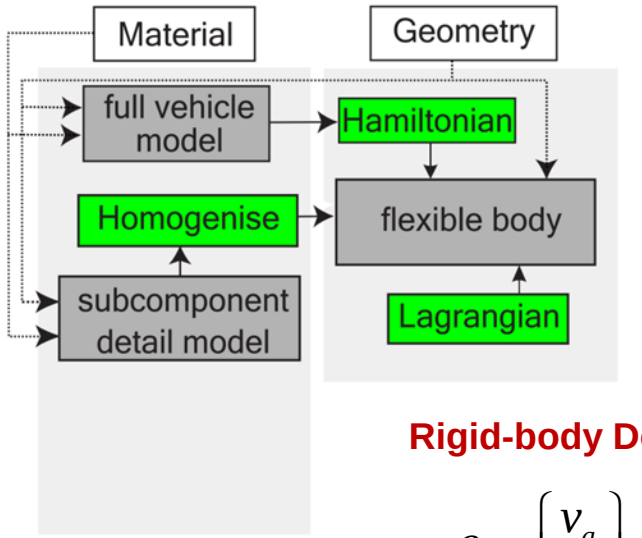
Condensation of large FE models*

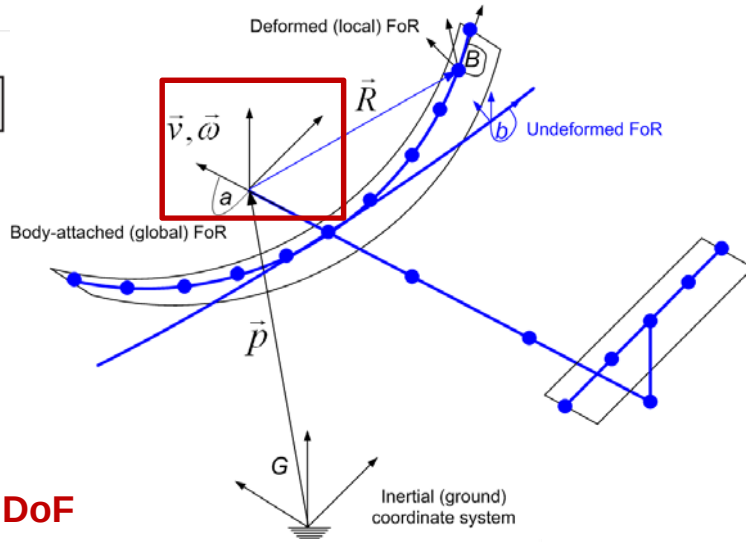


*Wang *et al.* **A Method for Normal-Mode-Based Model Reduction in Nonlinear Structural Dynamics,** under review

Imperial College London

SHARP.Beams: Geometrically-nonlinear composite beams





Rigid-body DoF

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

Structural DoF

$$\eta = \begin{Bmatrix} R_a \\ \Psi \end{Bmatrix}$$

at FE nodes

Nonlinear equations of motion

$$M(\eta)\begin{Bmatrix} \ddot{\eta} \\ \dot{\beta} \end{Bmatrix} + Q_{gyr}(\eta,\dot{\eta},\beta) + Q_{stif}(\eta) = Q_{ext}(\eta,\dot{\eta},\beta,\zeta)$$

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

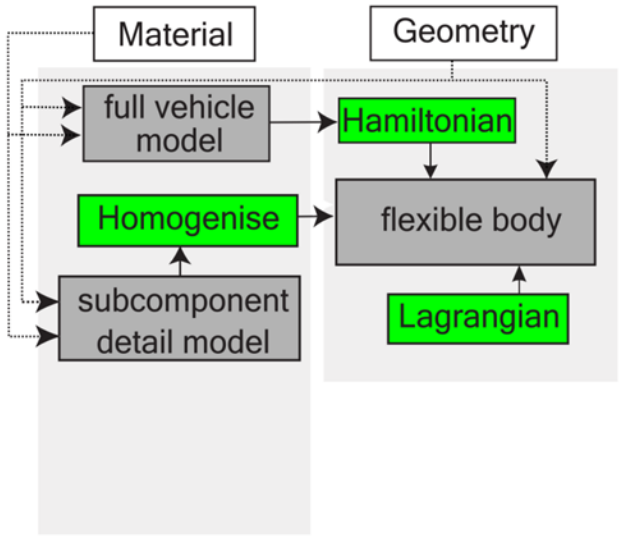
$$\dot{p}_a = v_a$$

Propagation of body-attached FoR

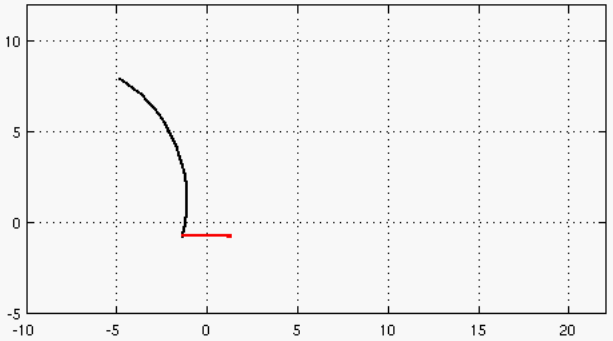
Linearized equations

$$\mathcal{M}(\eta_0)\begin{Bmatrix} \dot{\bar{\beta}} \\ \ddot{\bar{\eta}} \end{Bmatrix} + C_{gyr}(\eta_0,\beta_0)\begin{Bmatrix} \bar{\beta} \\ \dot{\bar{\eta}} \end{Bmatrix} + \mathcal{K}_{stiff}(\eta_0)\begin{Bmatrix} 0 \\ \bar{\eta} \end{Bmatrix} = \bar{Q}_{ext}$$

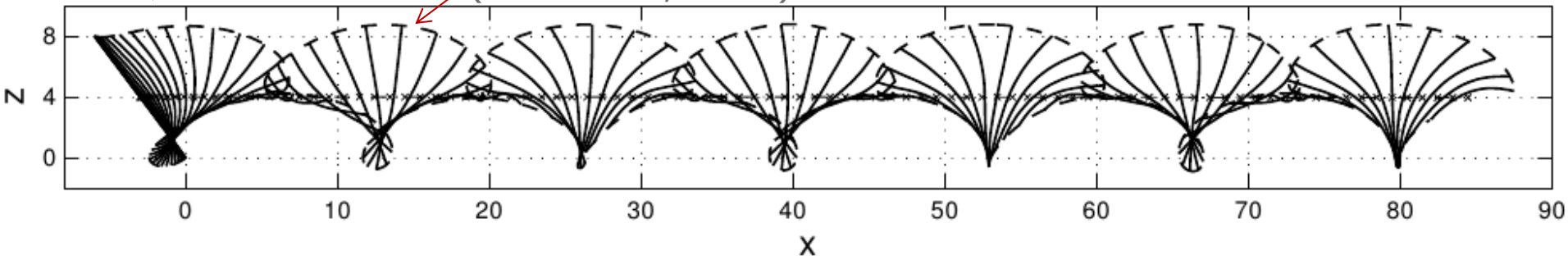
SHARP.Beams: Geometrically-nonlinear composite beams



Free-flying flexible beam in vacuum (no gravity)*

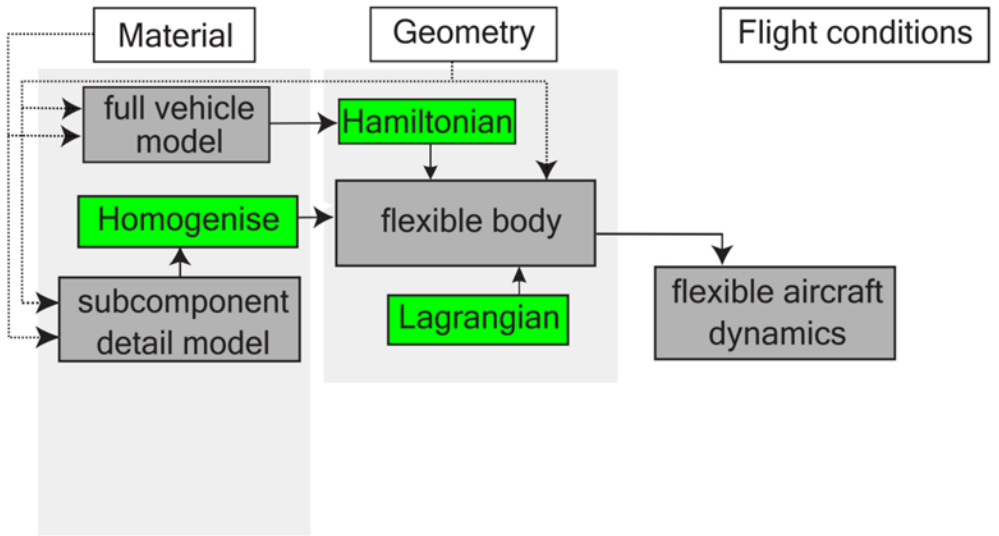


(Simo et al, 1988)

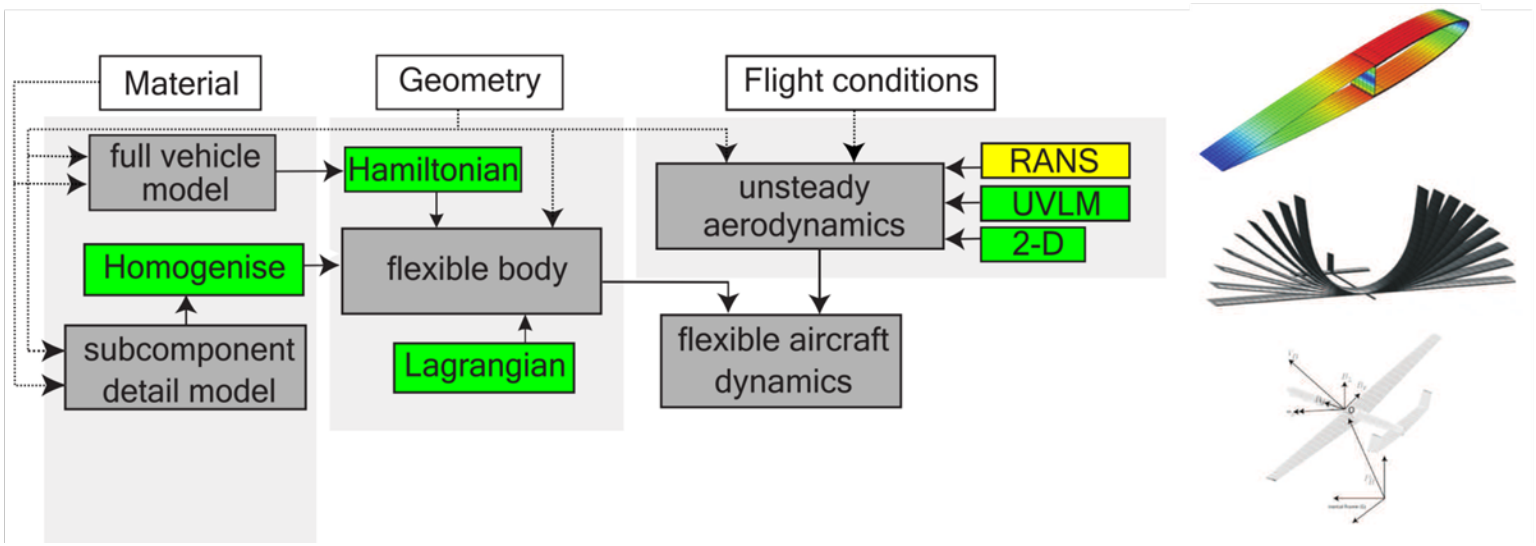


*Hesse, Palacios. **Consistent structural linearization in flexible-body dynamics with large rigid-body motion,** Comp&Struct 110 (2012)

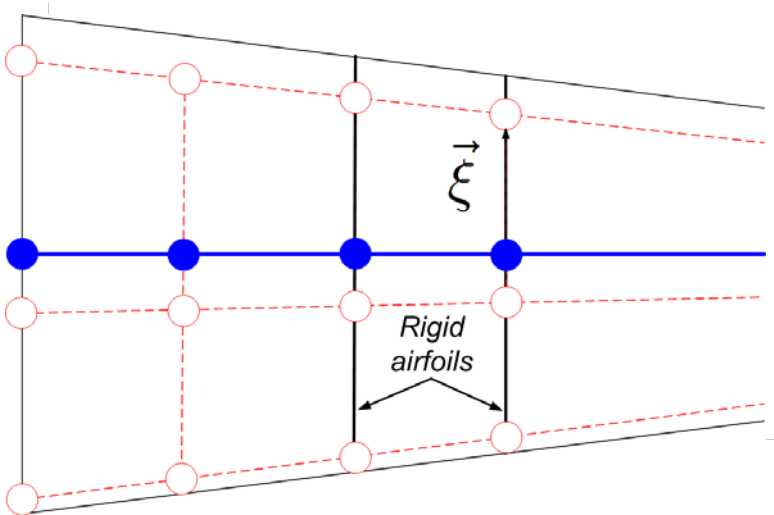
Flexible Vehicle Structural Dynamics



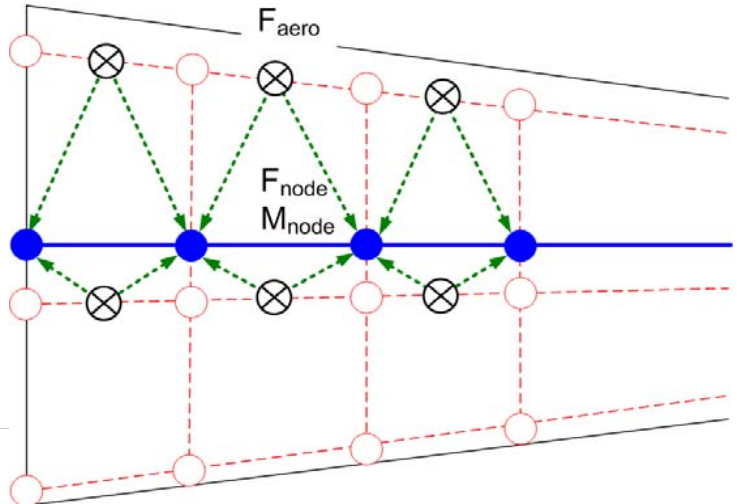
Adding the unsteady aerodynamics



Structure to Aerodynamics



Aerodynamics to structure



Unsteady Vortex Lattice Method (UVLM)

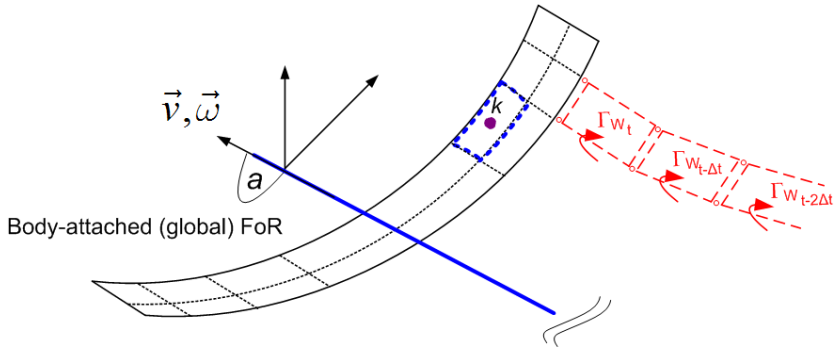
- Vortex-ring discretization (Katz & Plotkin, 2001)
- Potential flow, thin wing → Low speed flight, attached flow
- 3-D, unsteady, free-wake, interference, large (but slow) displacements

Propagation step:

$$A_b\boldsymbol{\Gamma}_b^{n+1} + A_w\boldsymbol{\Gamma}_w^{n+1} + \boldsymbol{w}^{n+1} = 0$$

$$\boldsymbol{\Gamma}_w^{n+1} = B_b\boldsymbol{\Gamma}_b^{n} + B_w\boldsymbol{\Gamma}_w^{n}$$

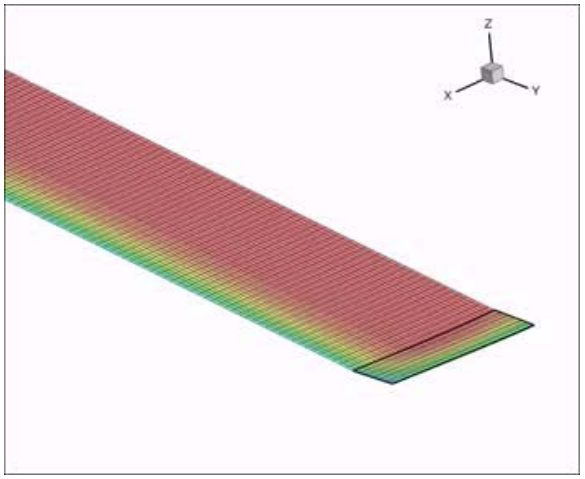
$$\boldsymbol{X}_w^{n+1} = C_b\boldsymbol{X}_b^{n+1} + C_w\boldsymbol{X}_w^{n} + \int_{t^n}^{t^{n+1}} \boldsymbol{V}(t)\,\mathrm{d}t$$



Output step*:

$$\delta\mathbf{F}_{st} = \rho_\infty\Gamma\left(\mathbf{U}\times\delta\mathbf{l}\right)$$

$$\mathbf{F}_{unst,k} = \rho_\infty\frac{\partial\Gamma_k}{\partial t}c\left(\hat{\mathbf{U}}\times\delta\mathbf{l}\right)$$



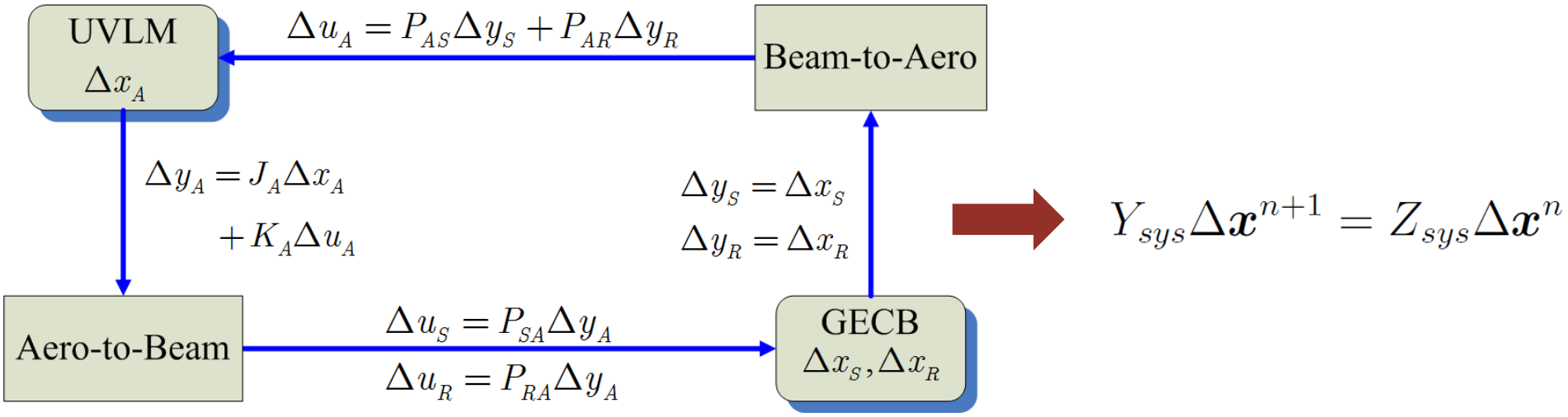
see movie

*Simpson *et al.* **Induced Drag Calculations in the Unsteady Vortex Lattice Method,** AIAA Journal **61** (2013)

Monolithic Coupling (linear problem)

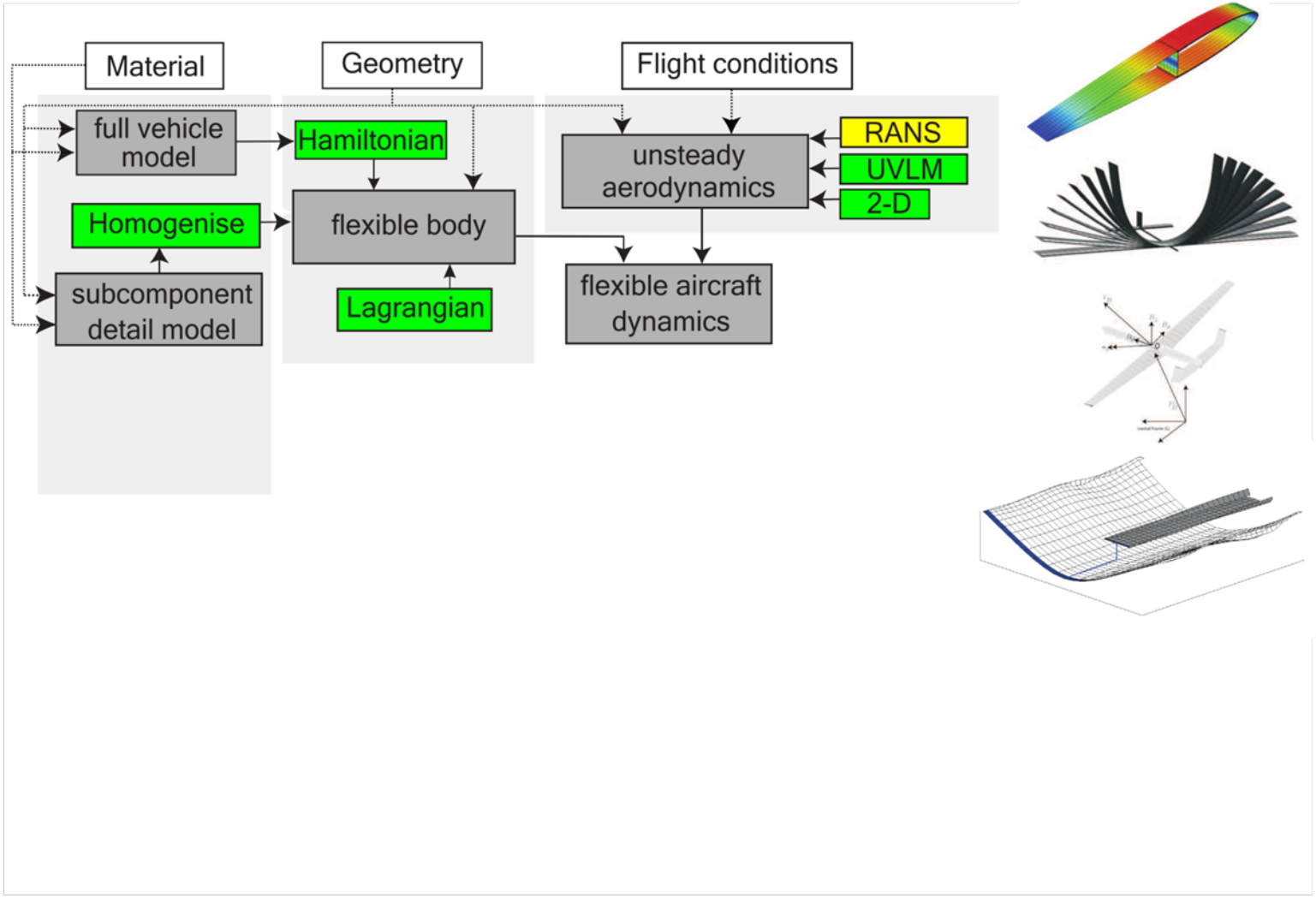
- Discrete-time state-space formulation*
- Linearization around given configuration (usually trim)
- Frozen geometry assumption → Prescribed wake

$$\boldsymbol{x} = \left[\boldsymbol{x}_A^T \mid \boldsymbol{x}_S^T \mid \boldsymbol{x}_R^T\right]^T = \left[\boldsymbol{\Gamma}_b^T \; \boldsymbol{\Gamma}_w^T \; \dot{\boldsymbol{\Gamma}}_b^T \mid \boldsymbol{\eta}^T \; \dot{\boldsymbol{\eta}}^T \mid v_a^T \; \omega_a^T \; \Phi^T\right]^T$$

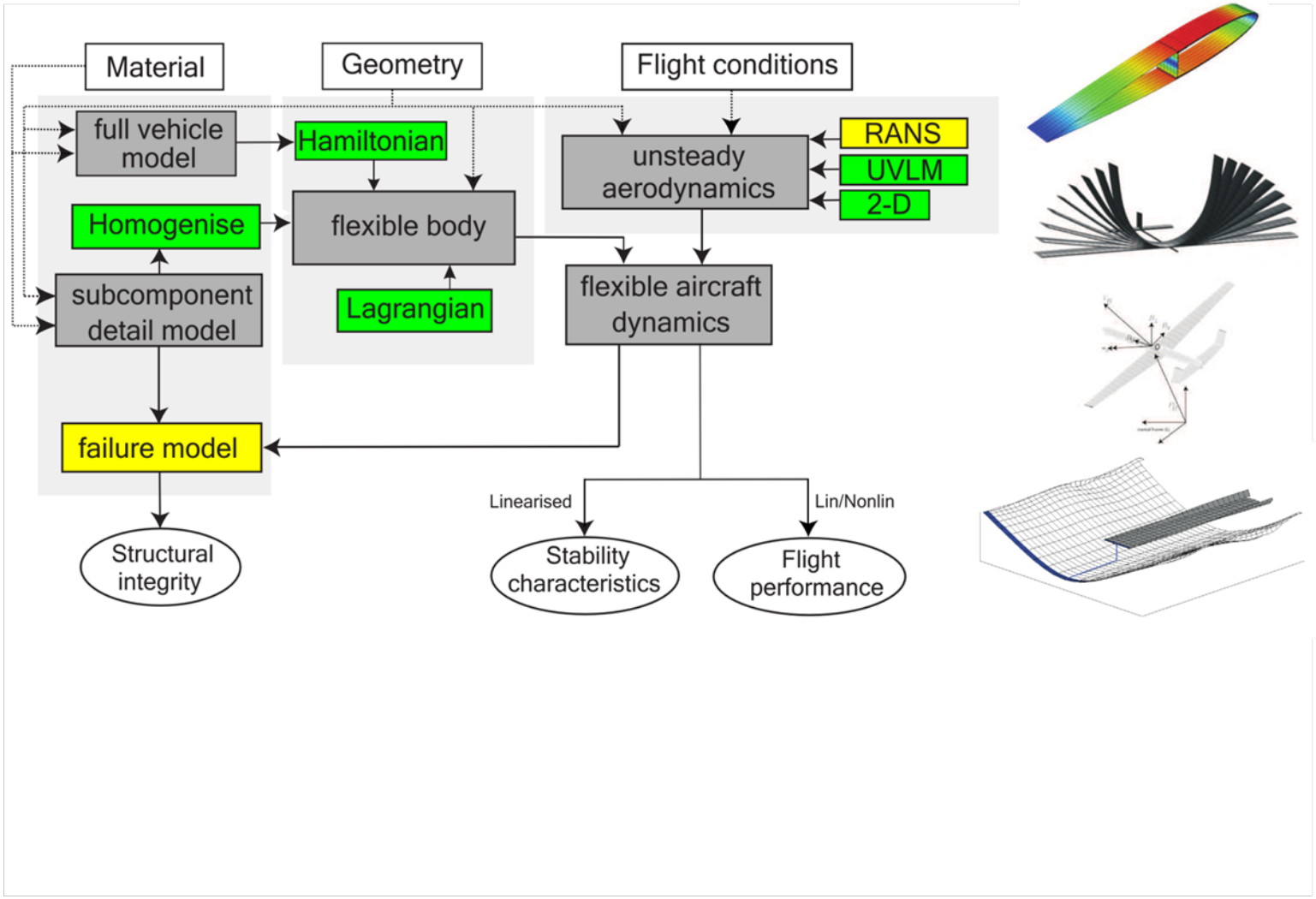


*Murua *et al.* **Applications of the unsteady vortex-lattice method in aircraft aeroelasticity and flight dynamics** JPAS 55 (2012)

Flexible aircraft dynamics (linear/nonlinear)

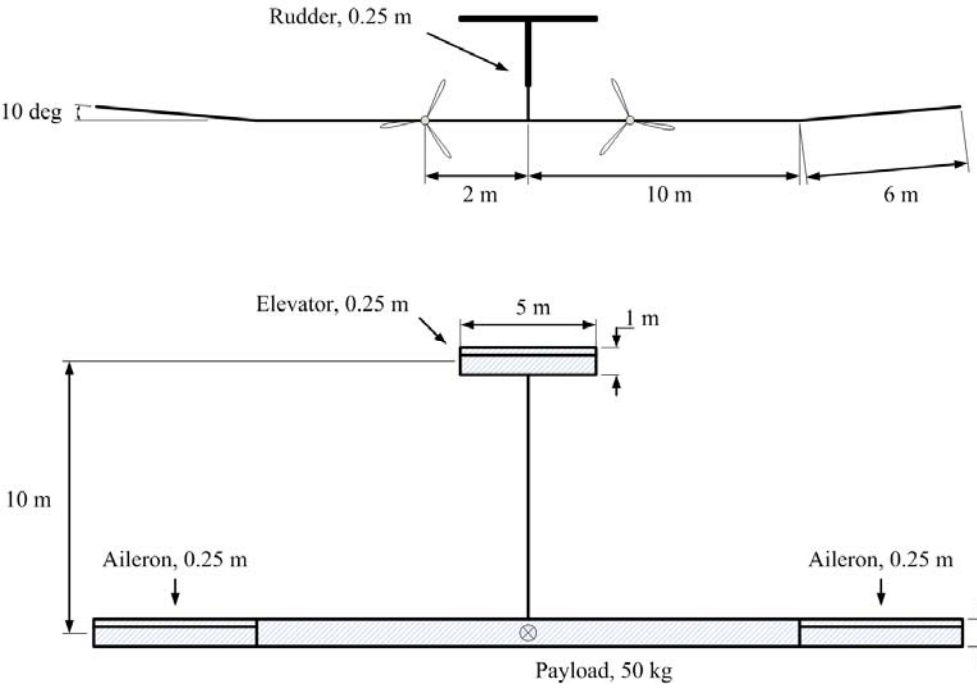


Flexible aircraft dynamics (linear/nonlinear)



Imperial College London

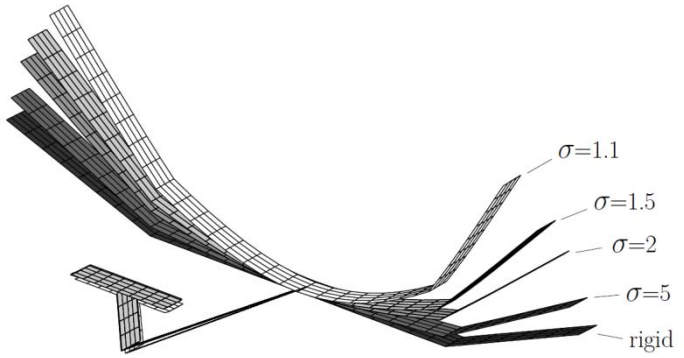
Stability of very light HALE UAV*



HALE model characteristics (Patil, 2001)	
Aspect ratio	16
Elastic axis (from le)	50 %
Center of gravity (from le)	50 %
Mass per unit length	0.75 kg/m
Torsional rigidity	$1\sigma \times 10^4$ N·m^2
Bending rigidity	$2\sigma \times 10^4$ N·m^2

σ: stiffness parameter

- Flexible main wing
- Rigid fuselage and T-tail
- Total mass: 75.4kg
- 20km altitude



Trim at V_∞=30m/s

*Hesse et al. (2014) **Consistent Structural Linearization in Flexible Aircraft Dynamics with Large Rigid-Body Motion,** AIAA Journal

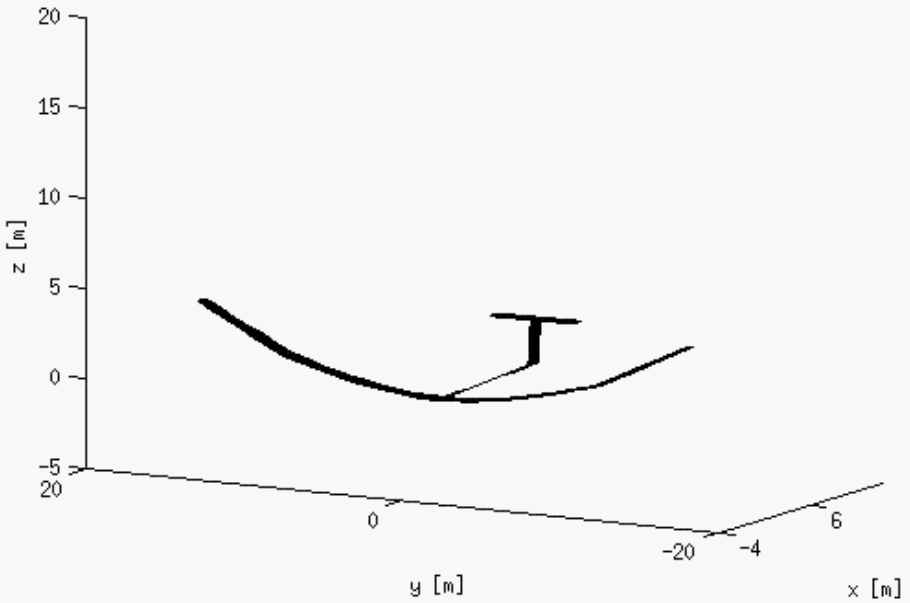
Imperial College London

Stability analysis of full aircraft

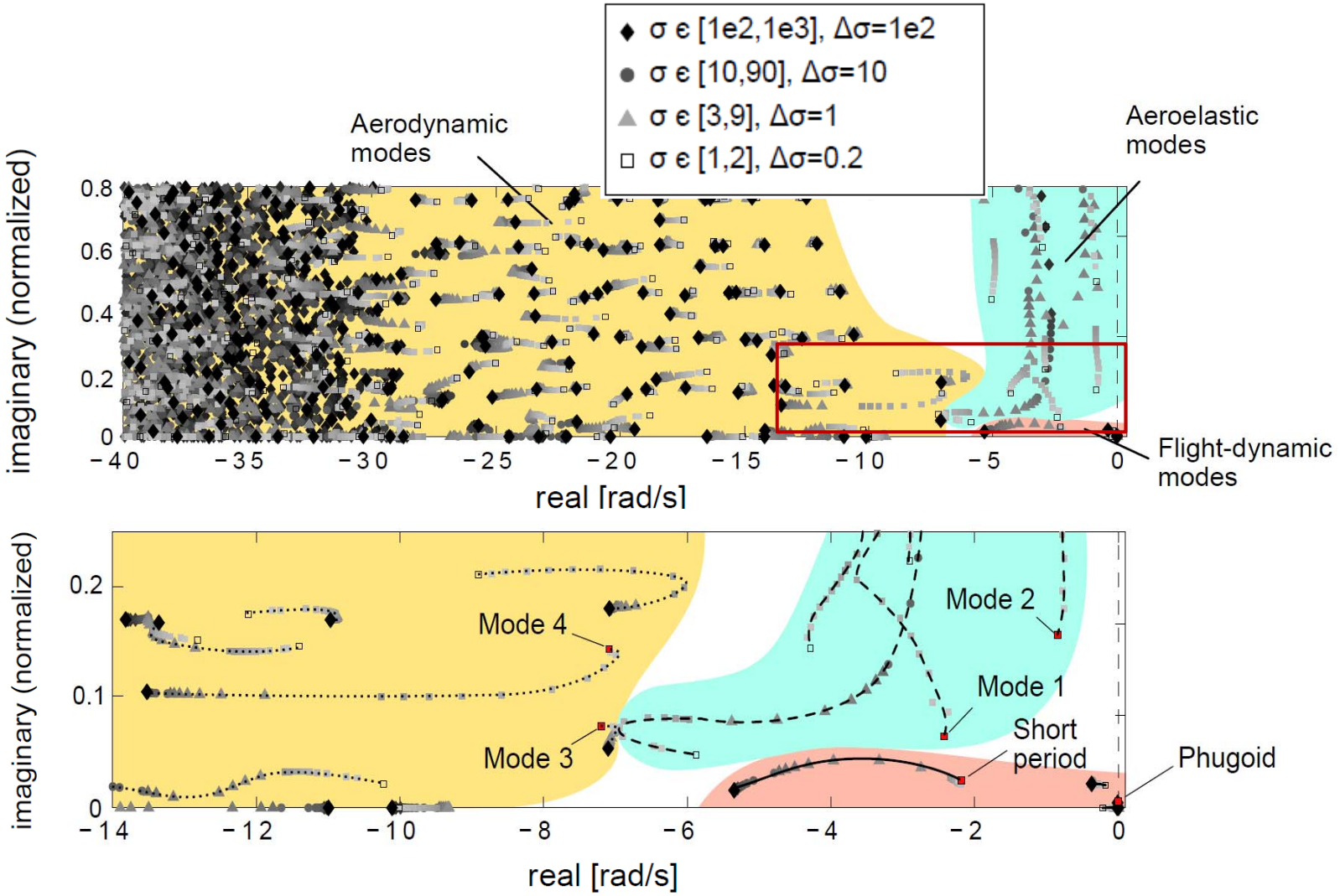
TRIM AIRCRAFT (Nonlinear) → LINEARIZE → DISCRETE-TIME SYSTEM MATRIX → EIGENVALUE ANALYSIS

	Phugoid	Short period	Spiral
Rigid	-0.011±0.27i	-4.53±1.67i	-0.064
Flexible	-0.0044±0.30i	**-2.18±1.57i**	-0.088

V_∞=30m/s
σ =2

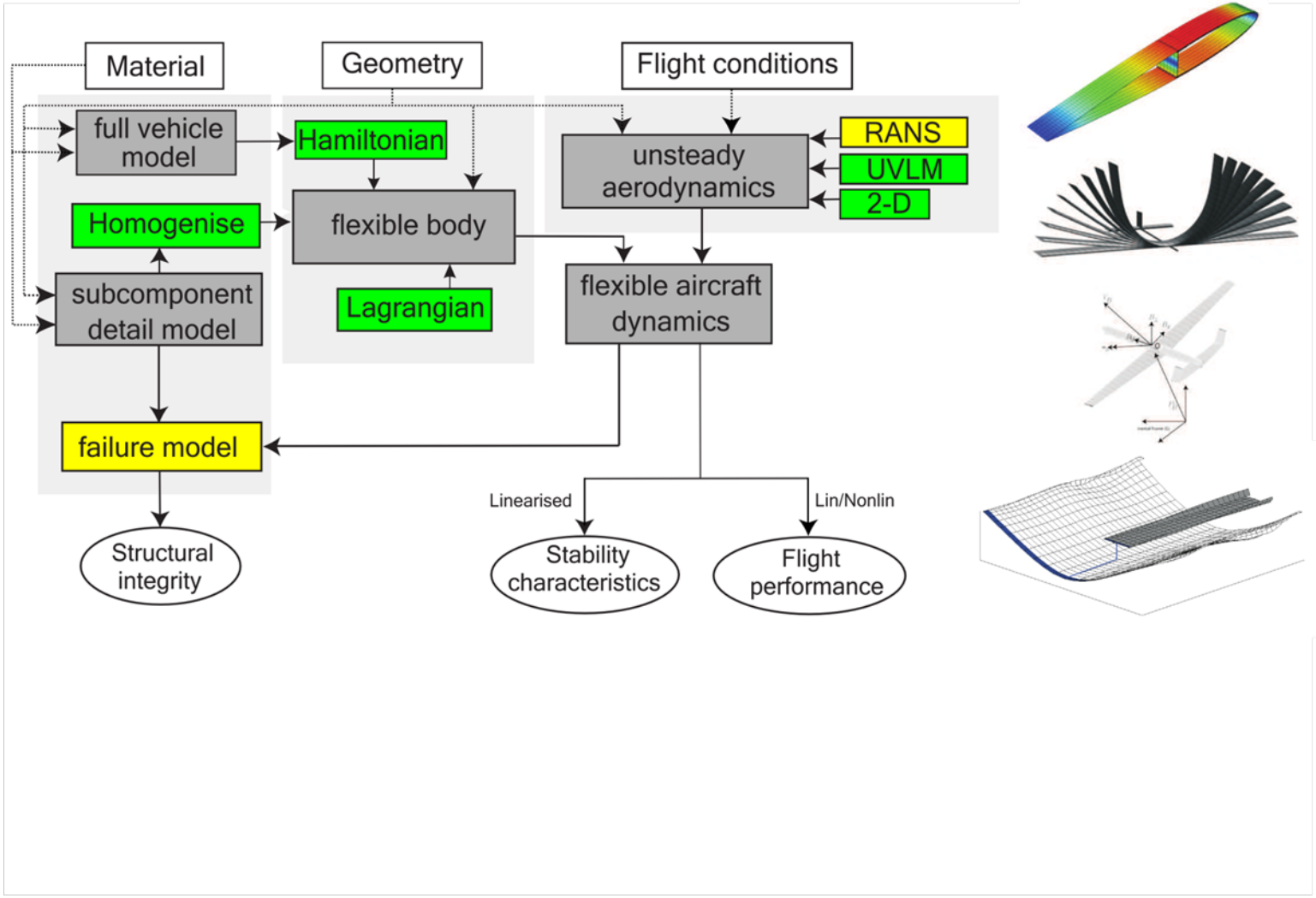


Dynamic stability vs. stiffness

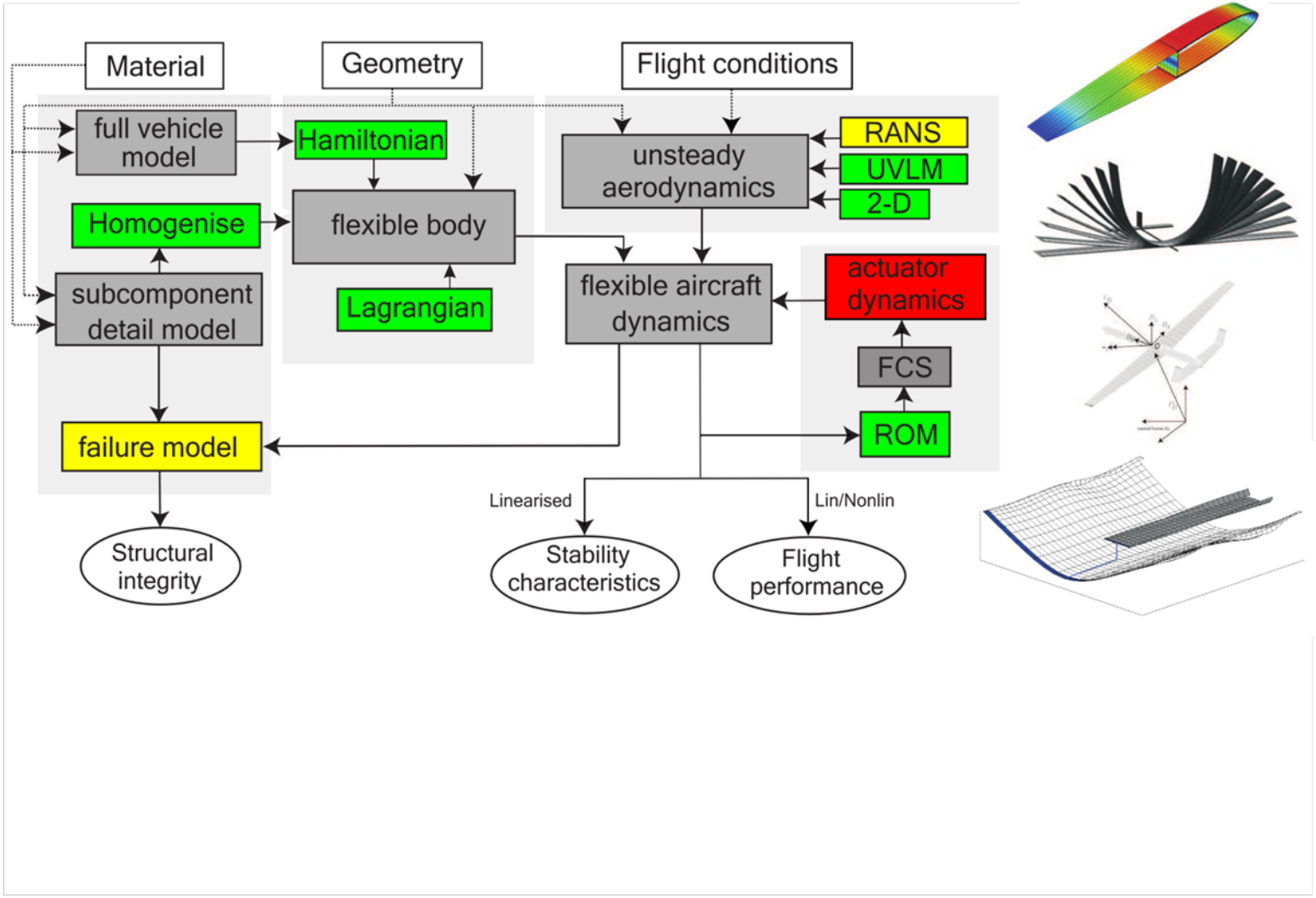


Dynamic stability directly from physical degrees of freedom

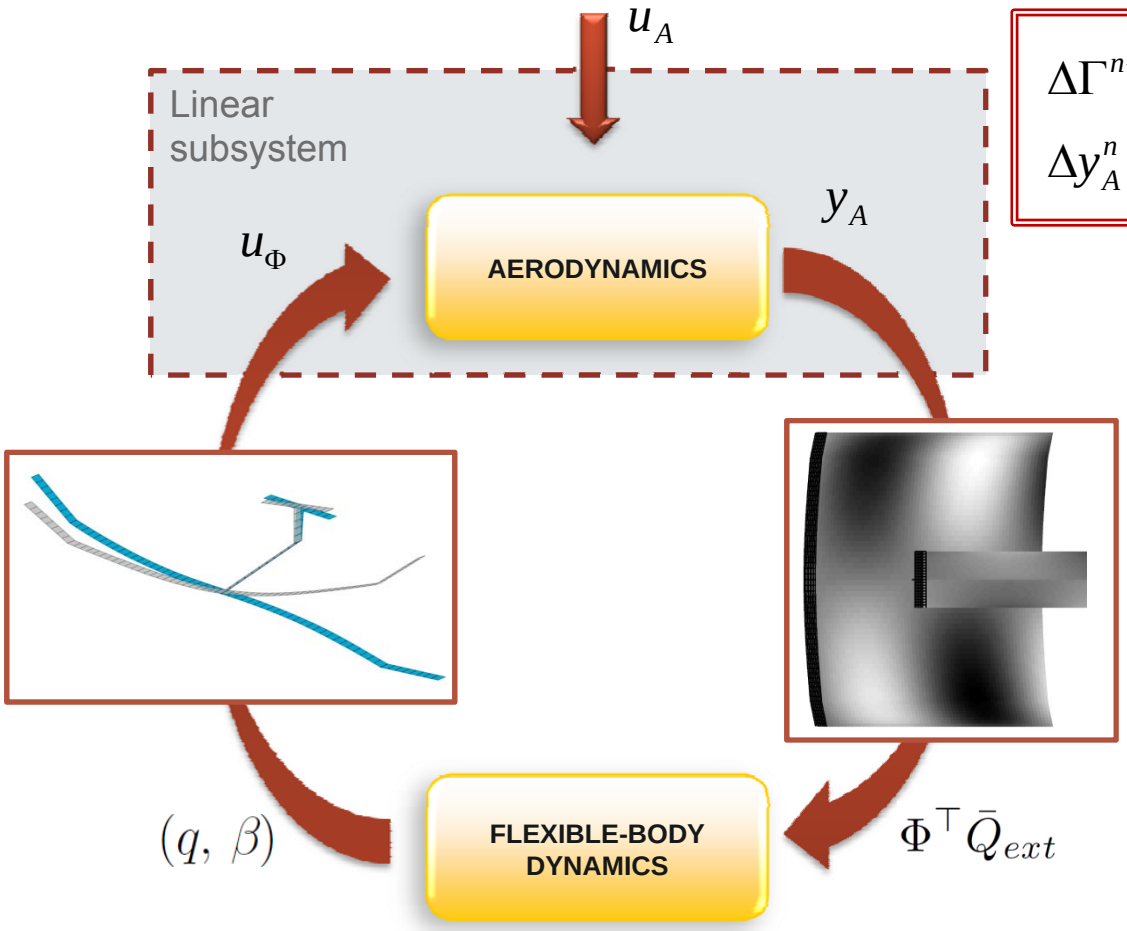
Closing the loop



Closing the loop



Dynamic aeroelasticity of manoeuvring aircraft

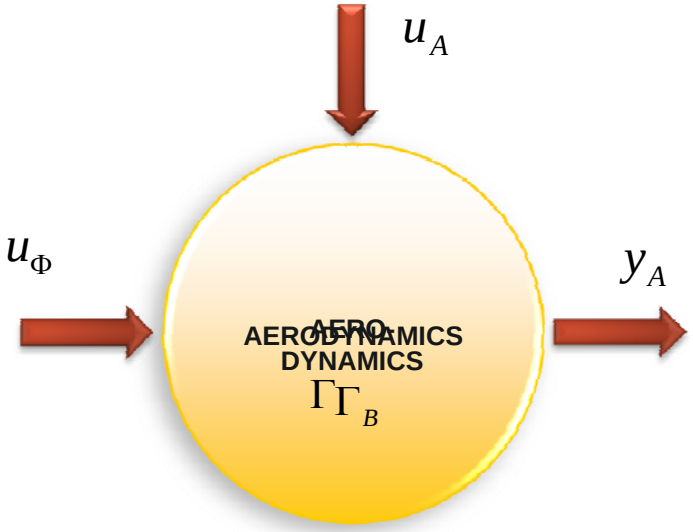


$$\Delta\Gamma^{n+1} = A\Delta\Gamma^n + B_S\Phi\Delta u_\Phi^n + B_A u_A^n$$
$$\Delta y_A^n = \Phi^T C\Delta\Gamma^n$$

$$\Phi^T M(\eta_0)\Phi \begin{Bmatrix}\ddot{q}\\ \dot{\beta}\end{Bmatrix} + \Phi^T \bar{C}(\eta_0,\beta)\Phi \begin{Bmatrix}\dot{q}\\ \beta\end{Bmatrix} + \Phi^T \bar{K}(\eta_0,\beta)\Phi \begin{Bmatrix}q\\ 0\end{Bmatrix} = \Phi^T Q_{ext}(q,\dot{q},\beta,\zeta)$$

Dynamic aeroelasticity of manoeuvring aircraft*

- Small number of inputs and outputs (structural modes + rigid body)
- Model reduction through balanced truncation
  - Balance aerodynamic states using controllability/observability Gramians
  - Truncate least controllable and observable states



$$\Delta\Gamma^{n+1} = A\Delta\Gamma^n + B_S\Phi\Delta u_\Phi^n + B_A u_A^n$$

$$\Delta y_A^n = \Phi^T C\Delta\Gamma^n$$

$$\Gamma = T\Gamma_B$$

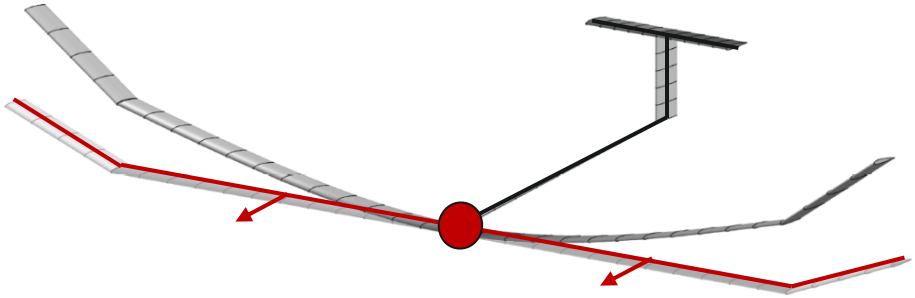
$$\Delta\Gamma_B^{n+1} = T^{-1}AT\Delta\Gamma_B^n + T^{-1}B_S\Phi\Delta u_\Phi^n + T^{-1}B_A u_A^n$$

$$\Delta y_A^n = \Phi^T CT\Delta\Gamma_B^n$$

*Hesse et al. **Reduced-Order Aeroelastic Models for the Dynamics of Maneuvering Flexible Aircraft**, AIAA Journal (2014)

Imperial College London

Load Alleviation for a HALE UAV

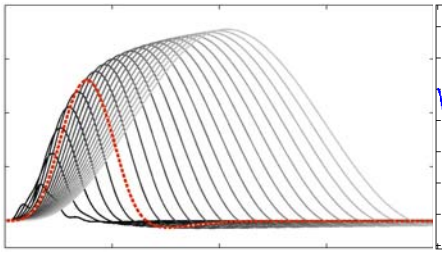


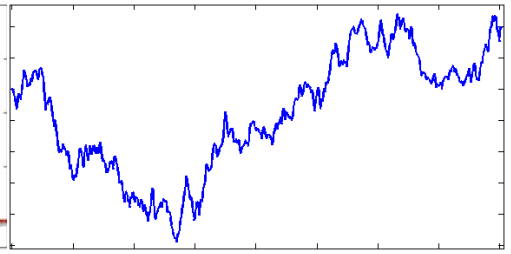
Composite beam → Nonlinear Trim → Dynamic Stability

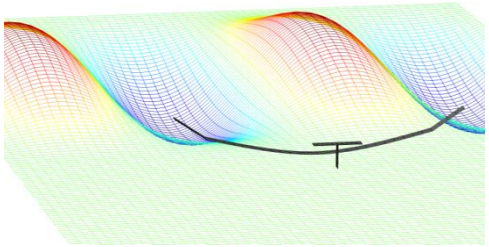
Hinf Synthesis ← Linear ROM ← Linear Plant

Load Alleviation ← Hinf Synthesis

Load Simulation ← Loads ROM ← Loads Plant

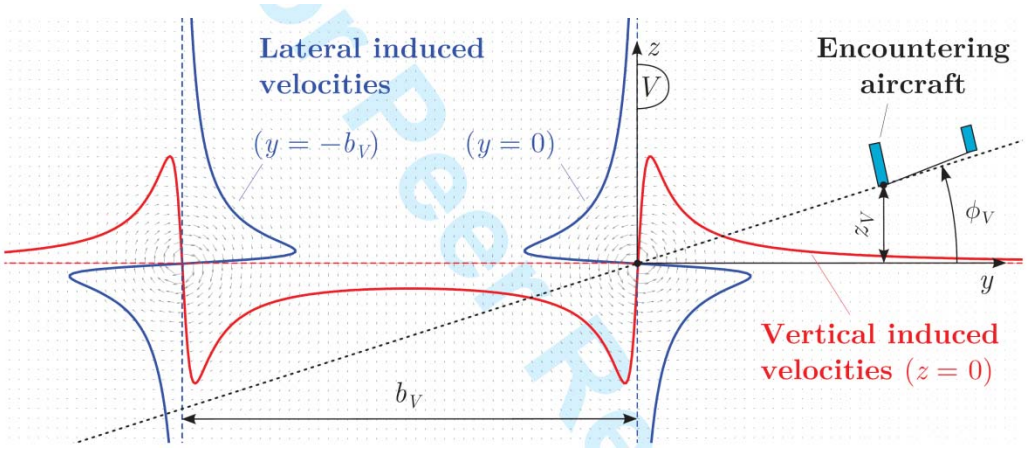


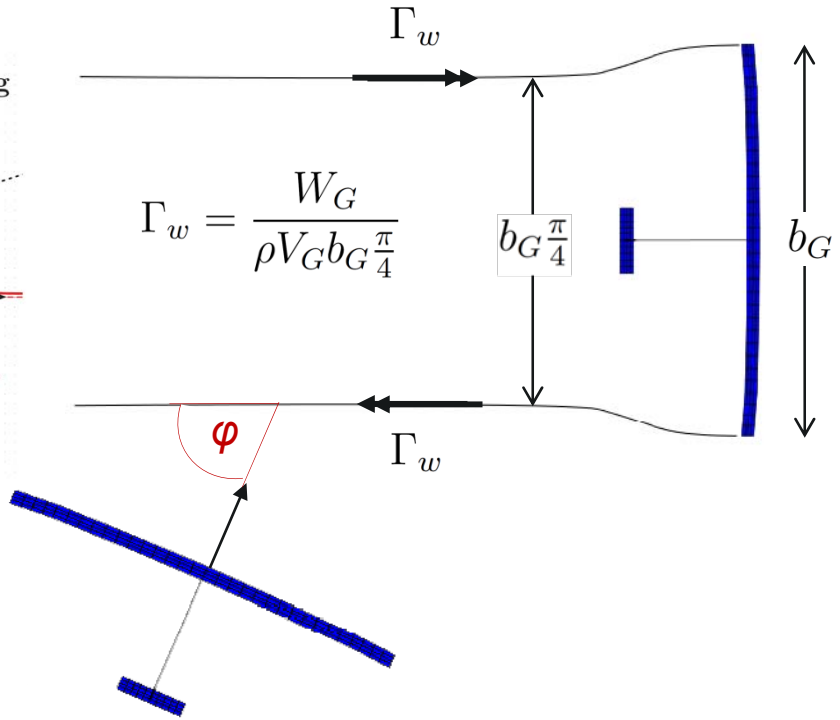




Imperial College London

Wake Vortex Encounters (WVE)





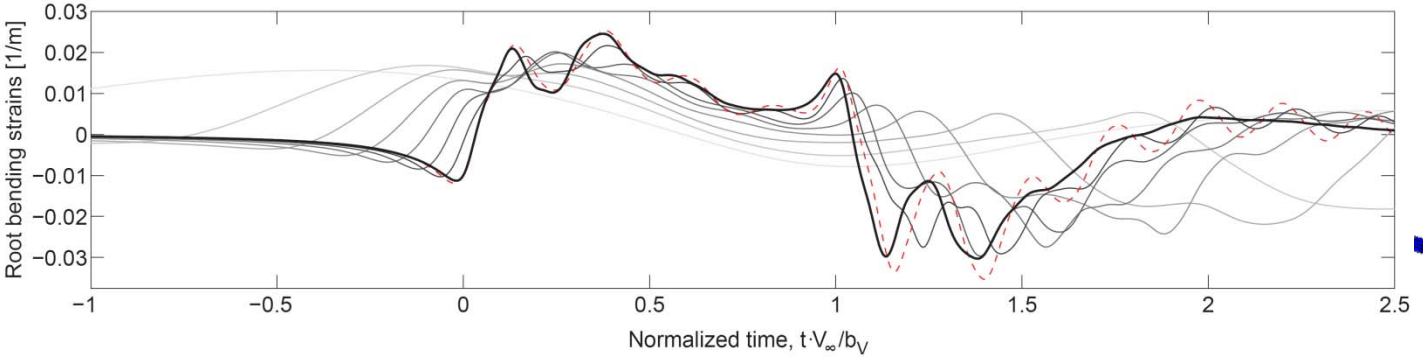
- Generating wake modelled following Kier (2011)
- Wake vortices modelled as vortex filaments from b_G= 50 m, W_G=2800 kg, V_G= 8 m/s
- Biot-Savart Law and exponential decay around viscous core radius

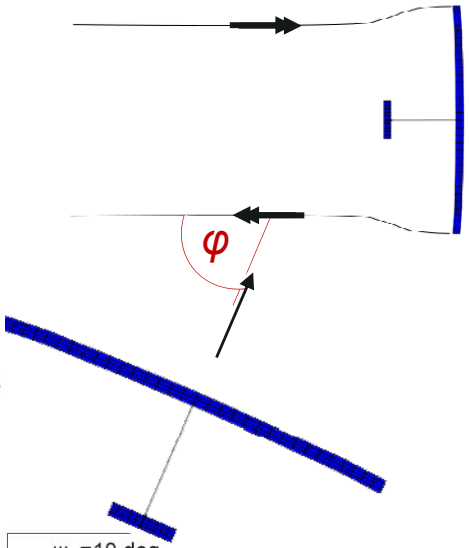
Kier, T, 2011. **An integrated loads analysis model including unsteady aerodynamic effects for position and attitude dependent gust fields**. IFASD 2011.

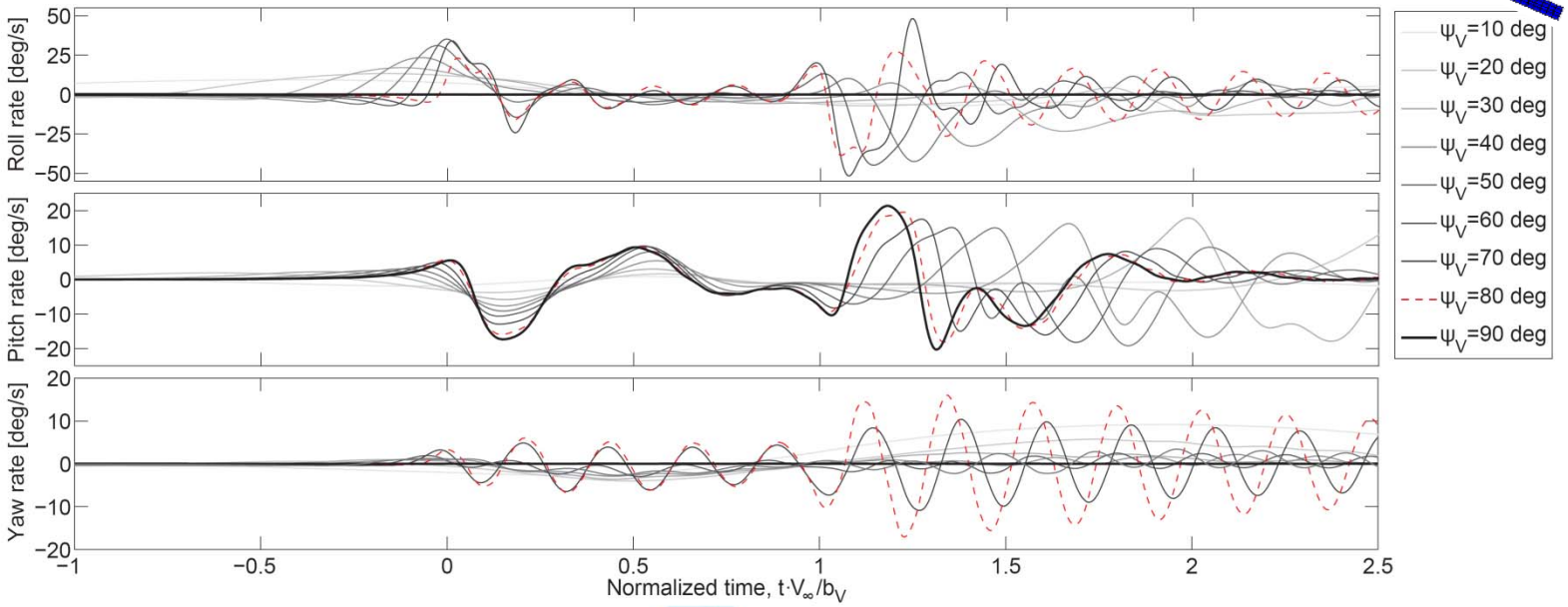
Are wake encounters important?

Imperial College London

Open-Loop results*



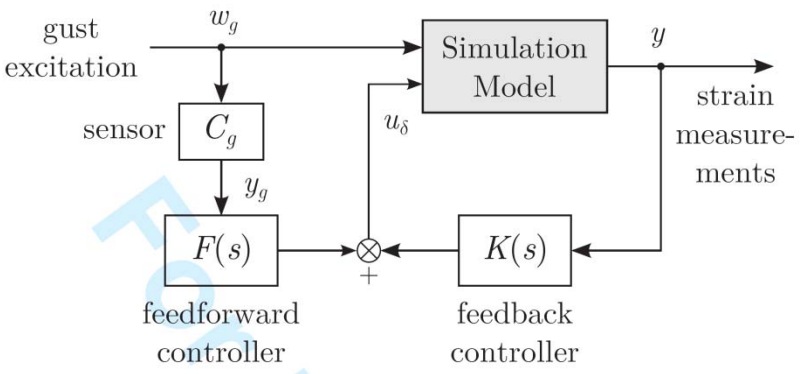




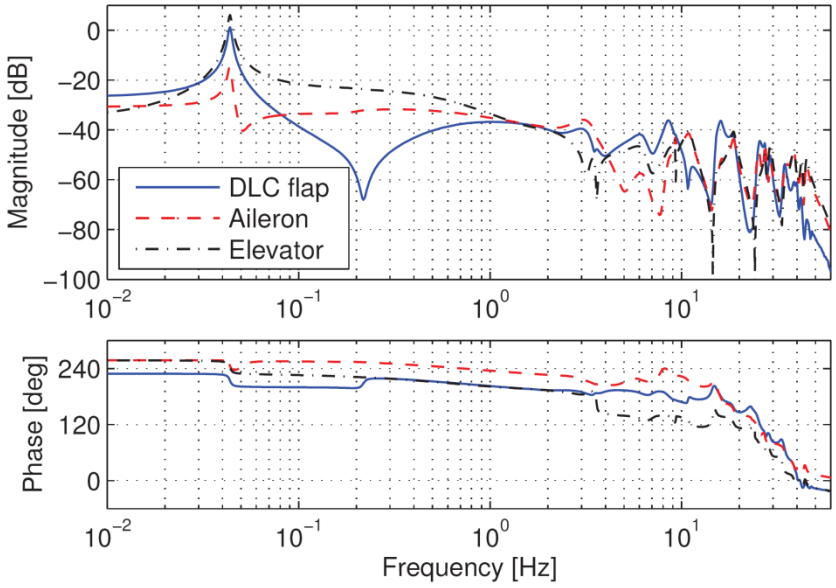
*Hesse and Palacios. **Dynamic Load Alleviation in Wake Vortex Encounters**, under review

Imperial College London

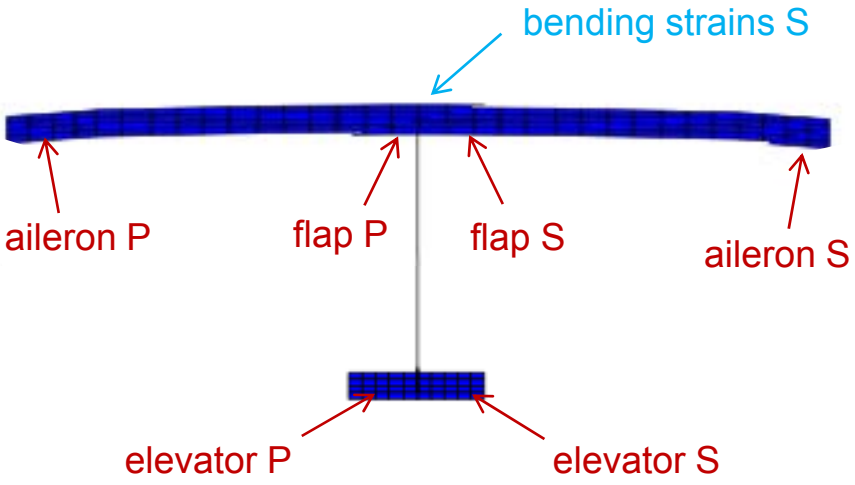
Hybrid control for load alleviation



- Linear ROM for control synthesis (50 states)
- H_∞ controller
- Robustness vs. performance (actuator constraints not in the model)



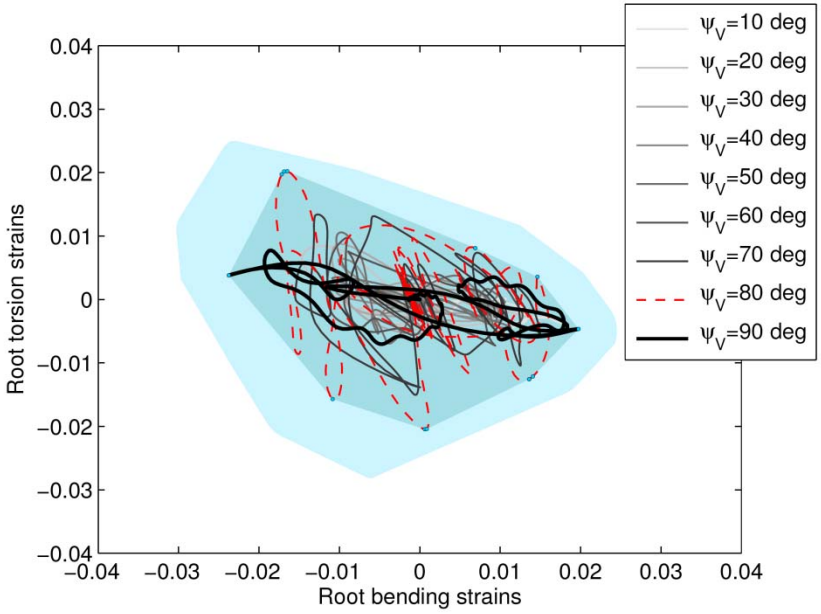
Control surface inputs to root bending strain



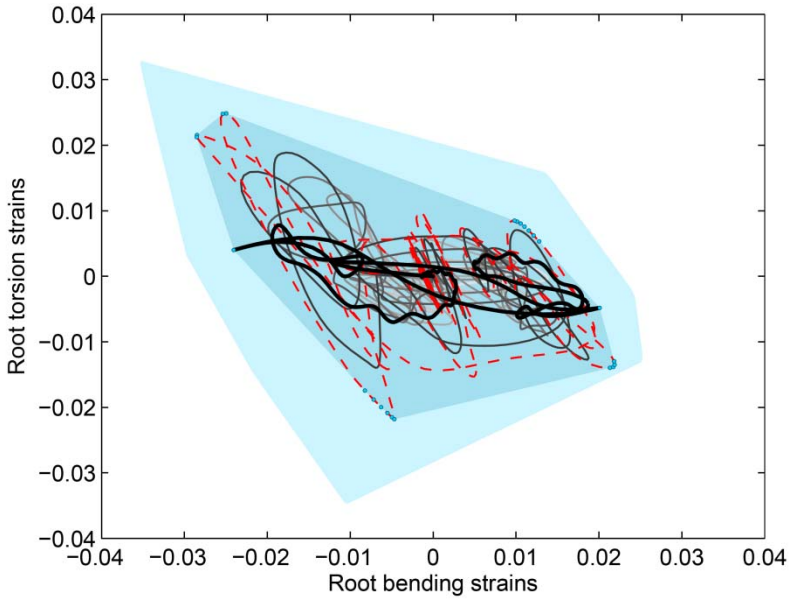
Hybrid control for load alleviation

- Load envelopes for open and close loop responses

Left wing



Right wing

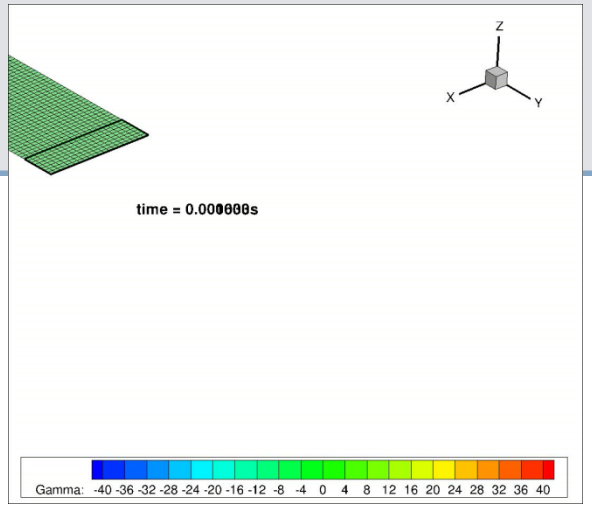


Effective approach for load alleviation → “less structure” → less weight

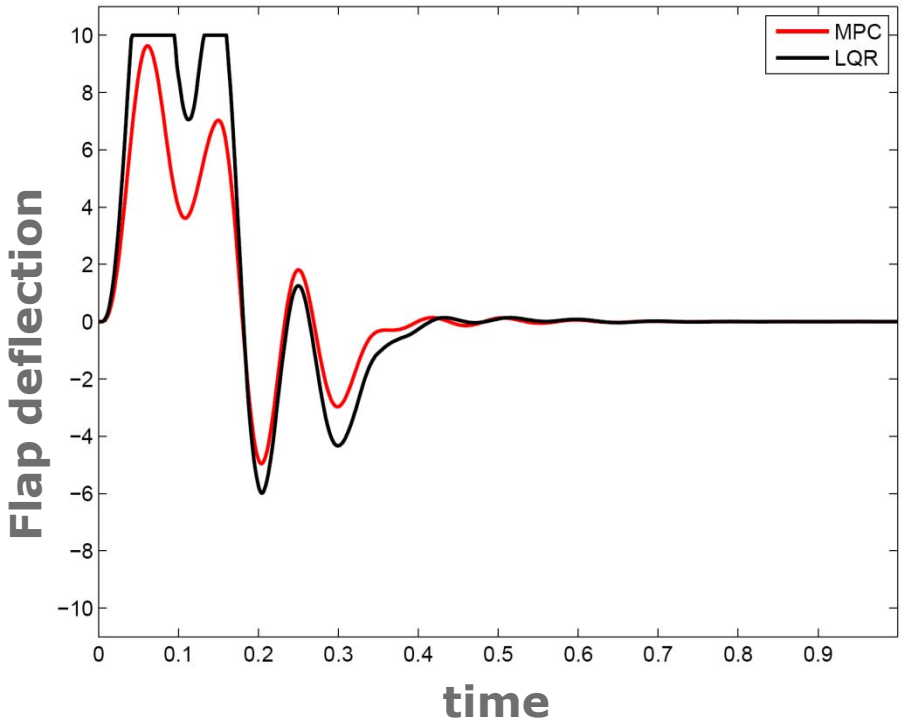
Imperial College London

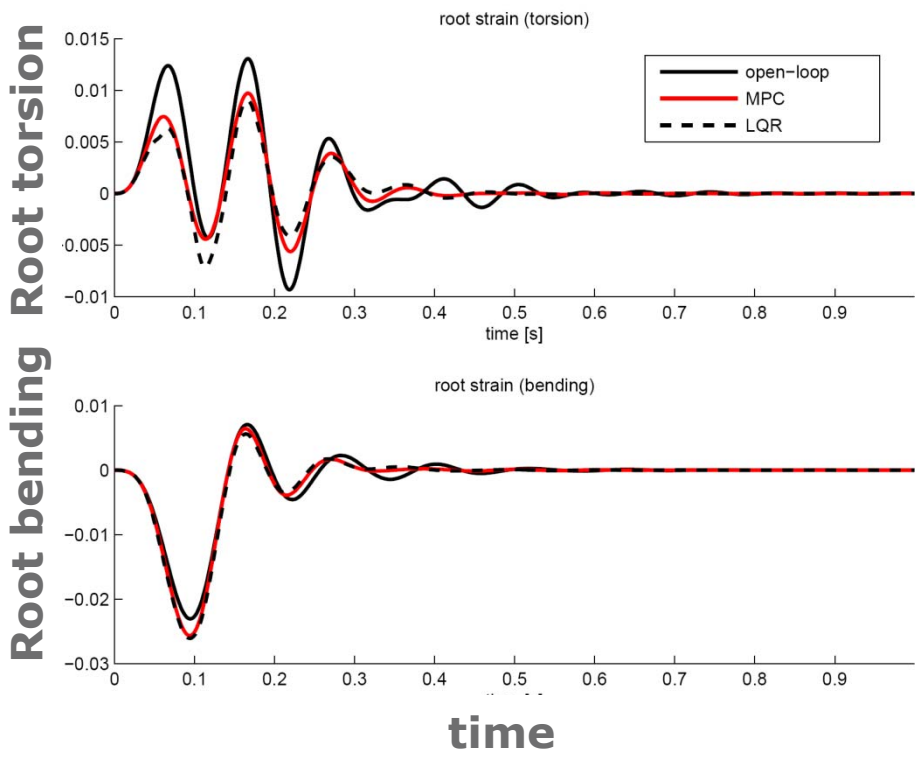
Towards Predictive Control

- “1-cos” gust on cantilever wing
- Control via trailing edge flap
- MPC vs. LQR with same weights



see movie



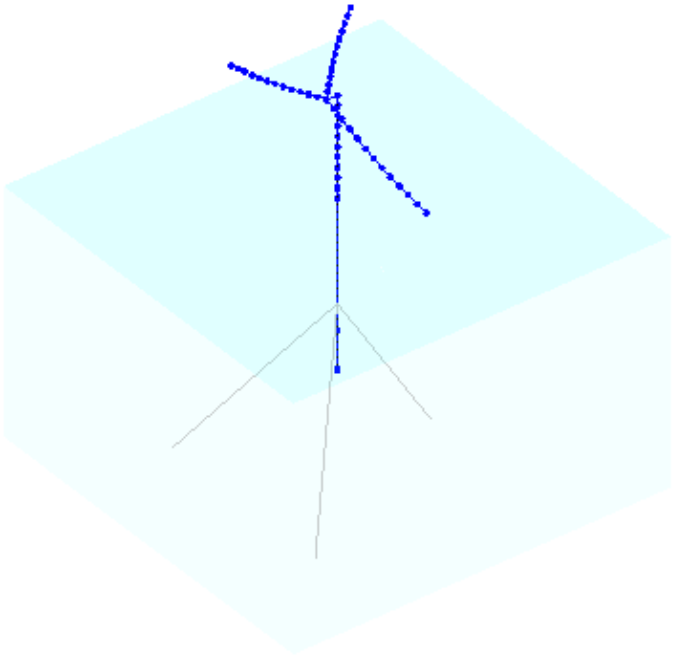


*Simpson et al. (2014). **Predictive Control for Alleviation of Gust Loads on Very Flexible Aircraft**. AIAA SciTech, Washington, DC

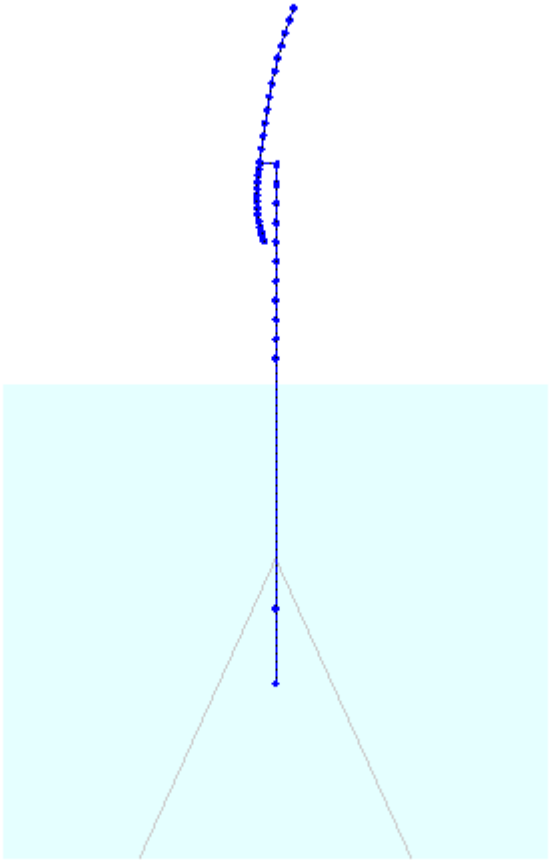
Imperial College London

Applications to wind energy*

- NREL 5-MW test case in storm (gusty wind and waves)
- Flaps actuated to reduce blade loads



see movie



see movie

*Ng et al. (2014) **Efficient Aeroservoelastic Modeling for the Control of Trailing-Edge Flaps on Wind Turbines,** UKACC

Conclusions

- Physics-based **state-space realizations** of 3-D aeroelasticity with potential-flow unsteady aerodynamics
- Coupling of rigid-body, structural, unsteady aerodynamics, and control system. Monolithic approach.
- integration of load alleviation strategies in Flight Control System
- Demonstration on Wake Encounter Loads
- On-going work:
  - Coupling with RANS (no longer monolithic!)
  - MPC implementation for simultaneous flight & load control