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Model Reduction in Flexible-Aircraft Dynamics with Large Rigid-Body Motion

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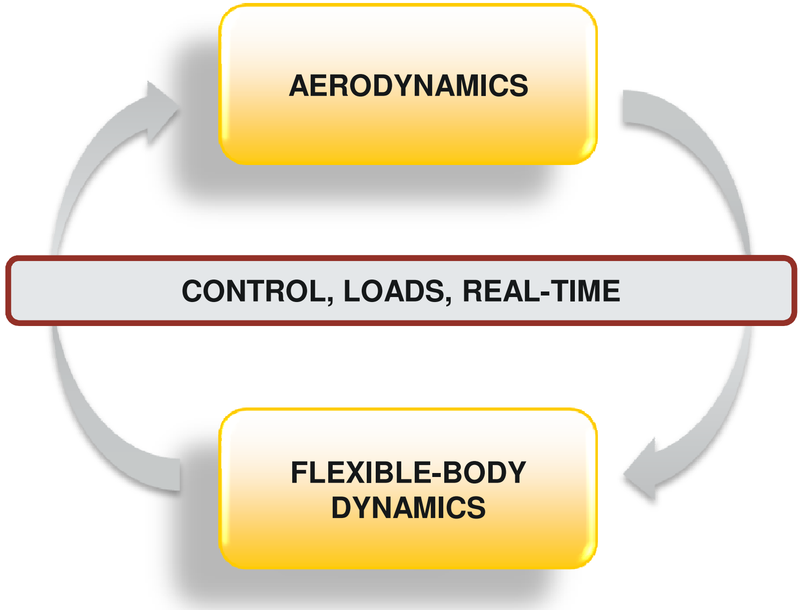
EPSRC Pioneering research and skills

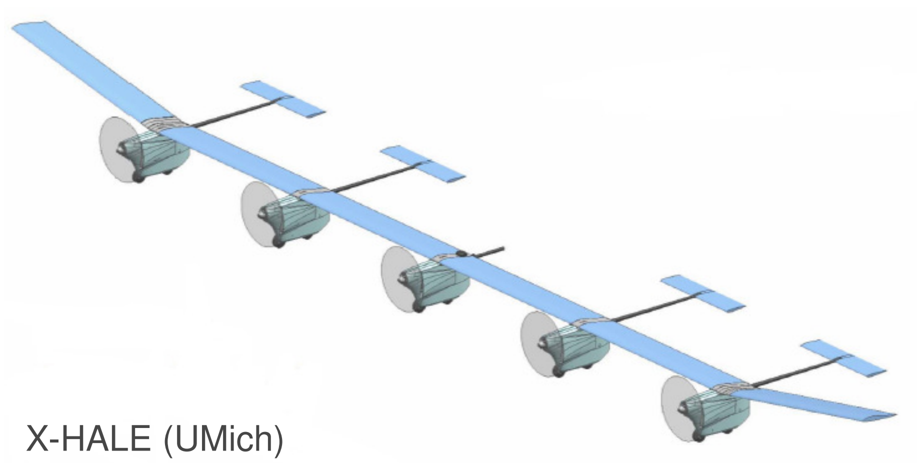
SDM Conference 2013 – Boston, USA – 11 April 2013

Flexibility = Barrier to high efficiency

- Next-generation aircraft design requires incorporation of flexibility effects on vehicle dynamics
- Aeroelastic modeling of maneuvering flexible aircraft:
  - Coupling effects between aircraft flexibility and flight dynamics?
  - Fidelity of the aerodynamic solution?
  - Can we include geometric nonlinearity?




SUGAR Volt (Boeing)


X-HALE (UMich)

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Modeling of Flexible Aircraft Dynamics

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- Aeroelastic modeling of maneuvering flexible aircraft:
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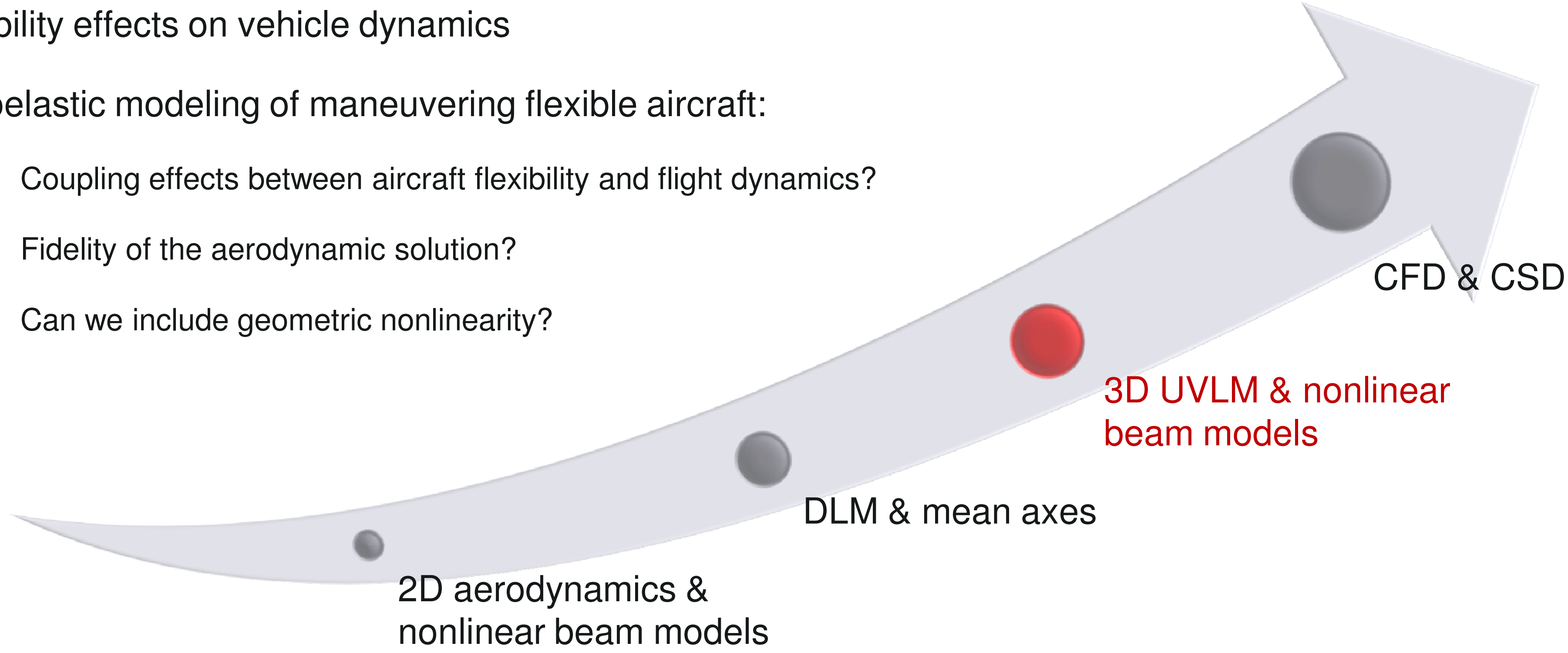
  - Can we include geometric nonlinearity?



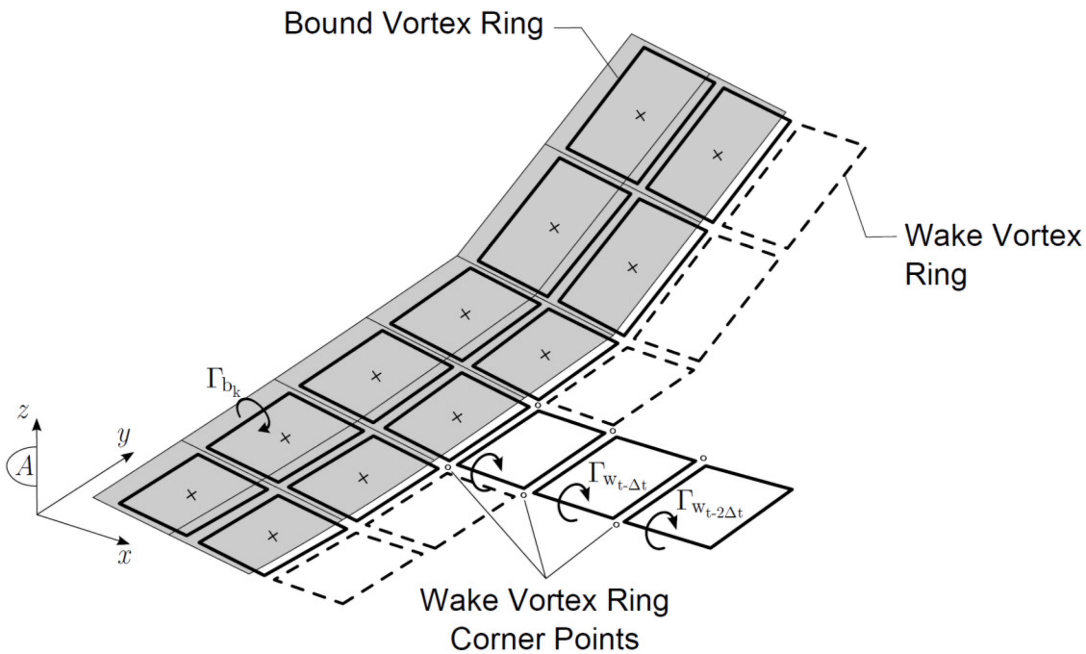
- Time-domain methods provide answers, but are computationally expensive with large system sizes
  - Required model fidelity and model reduction for control synthesis and load calculations?

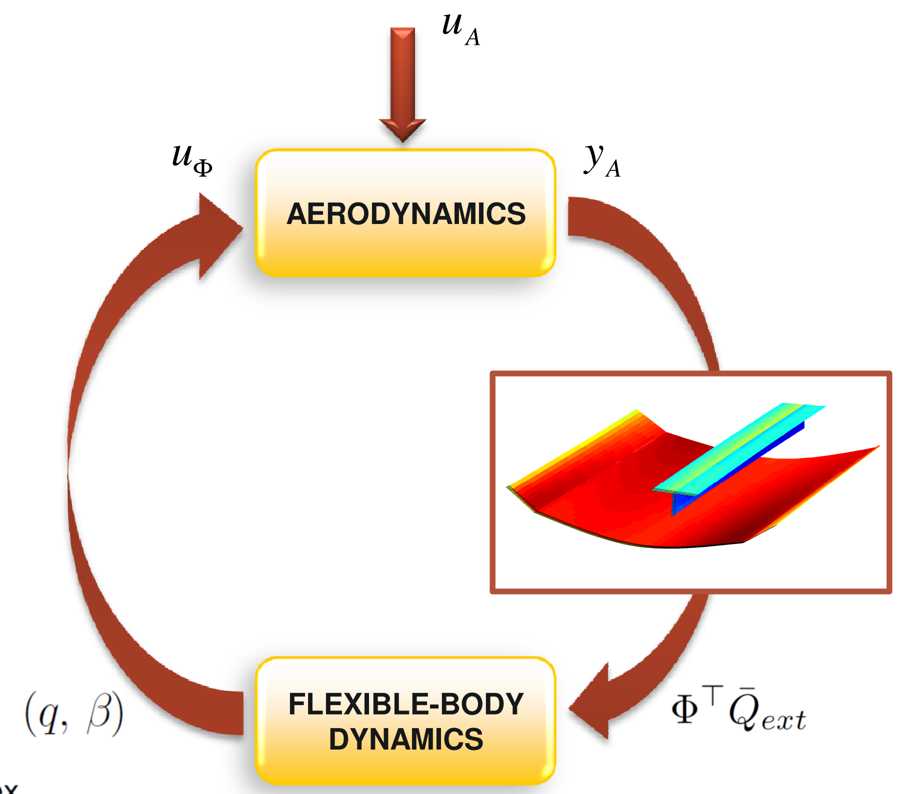
Aeroelastic system for maneuvering aircraft

$$\Delta\Gamma^{n+1} = A\Delta\Gamma^{n} + B_S\Phi\Delta u_\Phi^n + B_A u_A^n$$
$$\Delta y_A^n = \Phi^{\mathrm{T}}\left(C\Delta\Gamma^n + D_S\Phi\Delta u_\Phi^n + D_A u_A^n\right)$$

Linearised UVLM[1]

- Small deformations and velocities
- Low speed maneuvers





[1]Murua J, Palacios R, Graham JMR, 2012. **Applications of the unsteady vortex-lattice method in aircraft aeroelasticity and flight dynamics**, *JPAS* 55.

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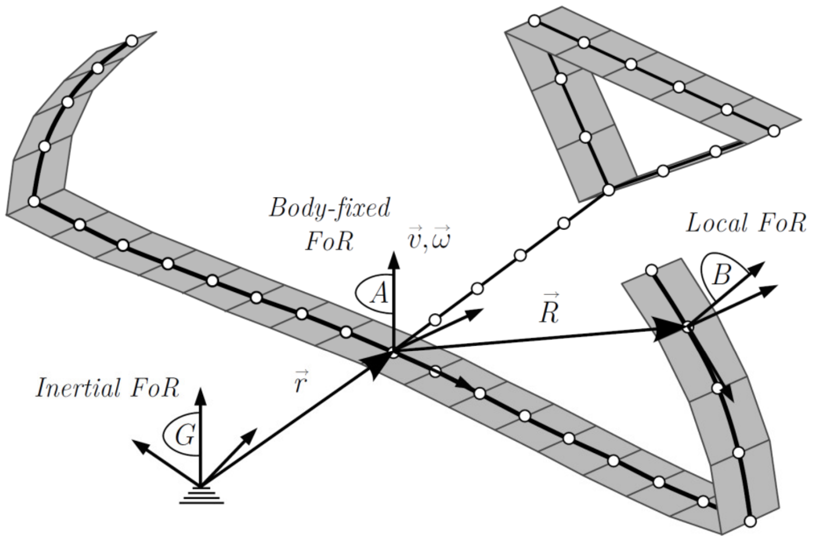
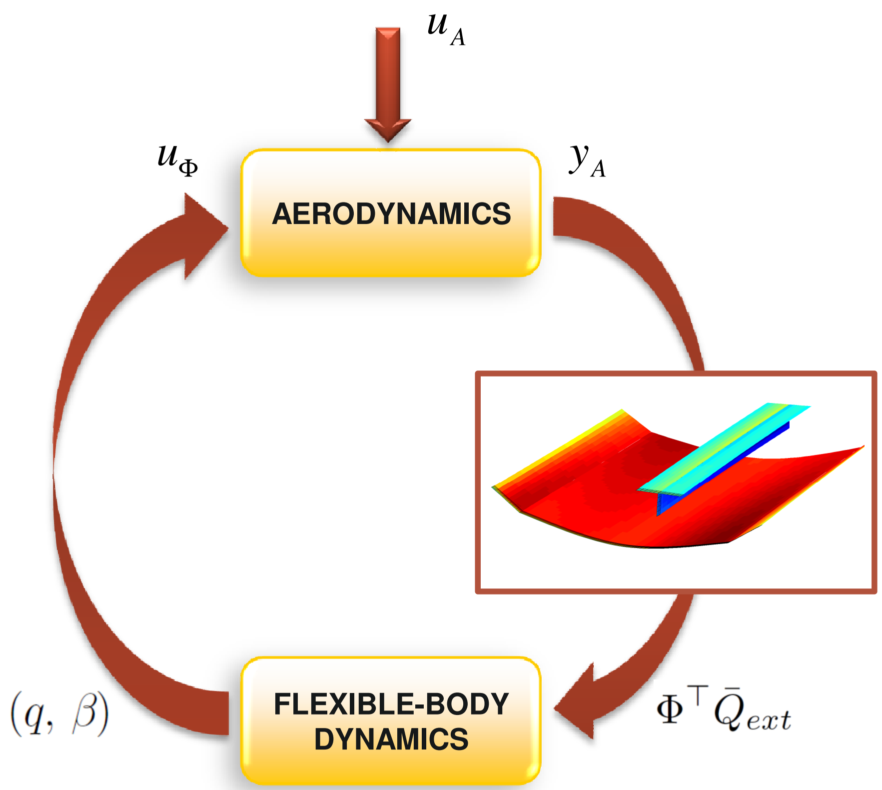
Aeroelastic system for maneuvering aircraft

Perturbation flexible-body dynamics

- Composite beam elements on a moving **body-attached** reference frame
- Linearisation of **structural** DoF around nonlinear trim configuration η_0





Equation of motion

$$M(\eta_0)\begin{Bmatrix}\ddot{\bar{\eta}}\\ \dot{\beta}\end{Bmatrix}+\bar{C}(\eta_0,\beta)\begin{Bmatrix}\dot{\bar{\eta}}\\ \beta\end{Bmatrix}+\bar{K}(\eta_0,\beta)\begin{Bmatrix}\bar{\eta}\\ 0\end{Bmatrix}=\bar{Q}_{ext}\left(\bar{\eta},\dot{\bar{\eta}},\beta,\zeta\right)$$

Rigid-body DoF

$$\beta=\begin{Bmatrix}v_A\\ \omega_A\end{Bmatrix}$$

Structural DoF

$$\bar{\eta}=\begin{Bmatrix}\bar{R}_A\\ \bar{\Psi}\end{Bmatrix}$$

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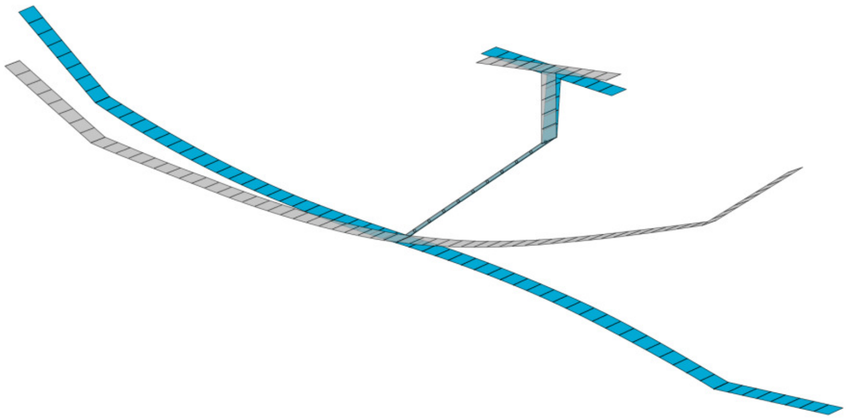
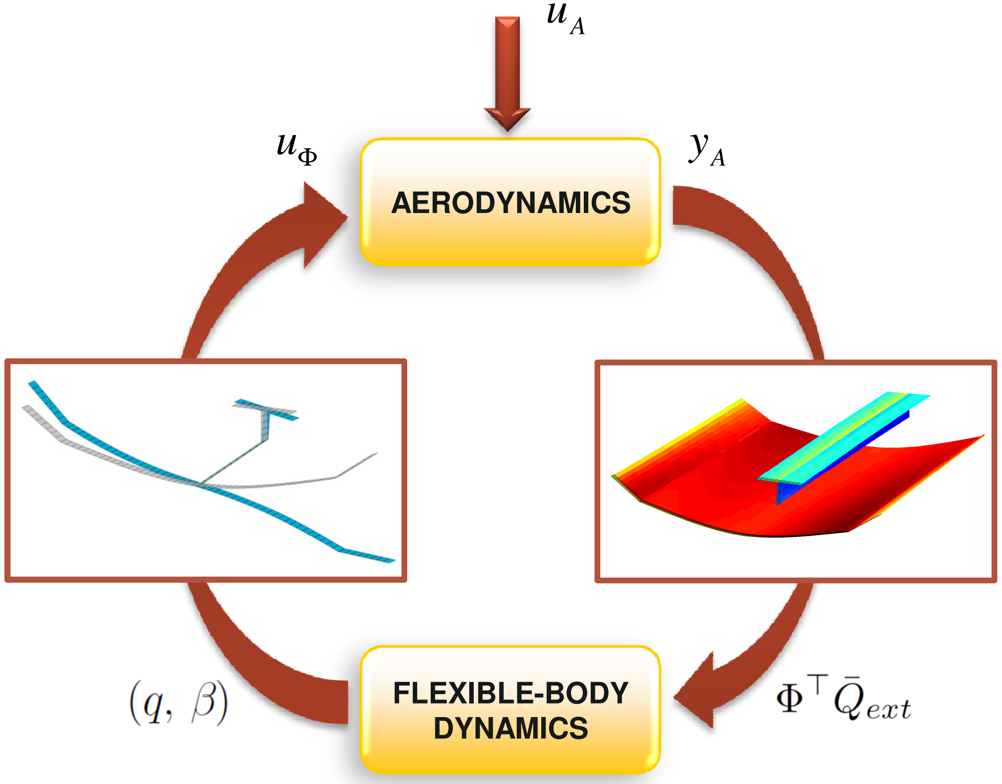
Aeroelastic system for maneuvering aircraft

Perturbation flexible-body dynamics

- Composite beam elements on a moving **body-attached** reference frame
- Linearisation of **structural** DoF around nonlinear trim configuration η_0
- Truncate number of generalised coordinates passed to the aerodynamic system





Equation of motion in modal form

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

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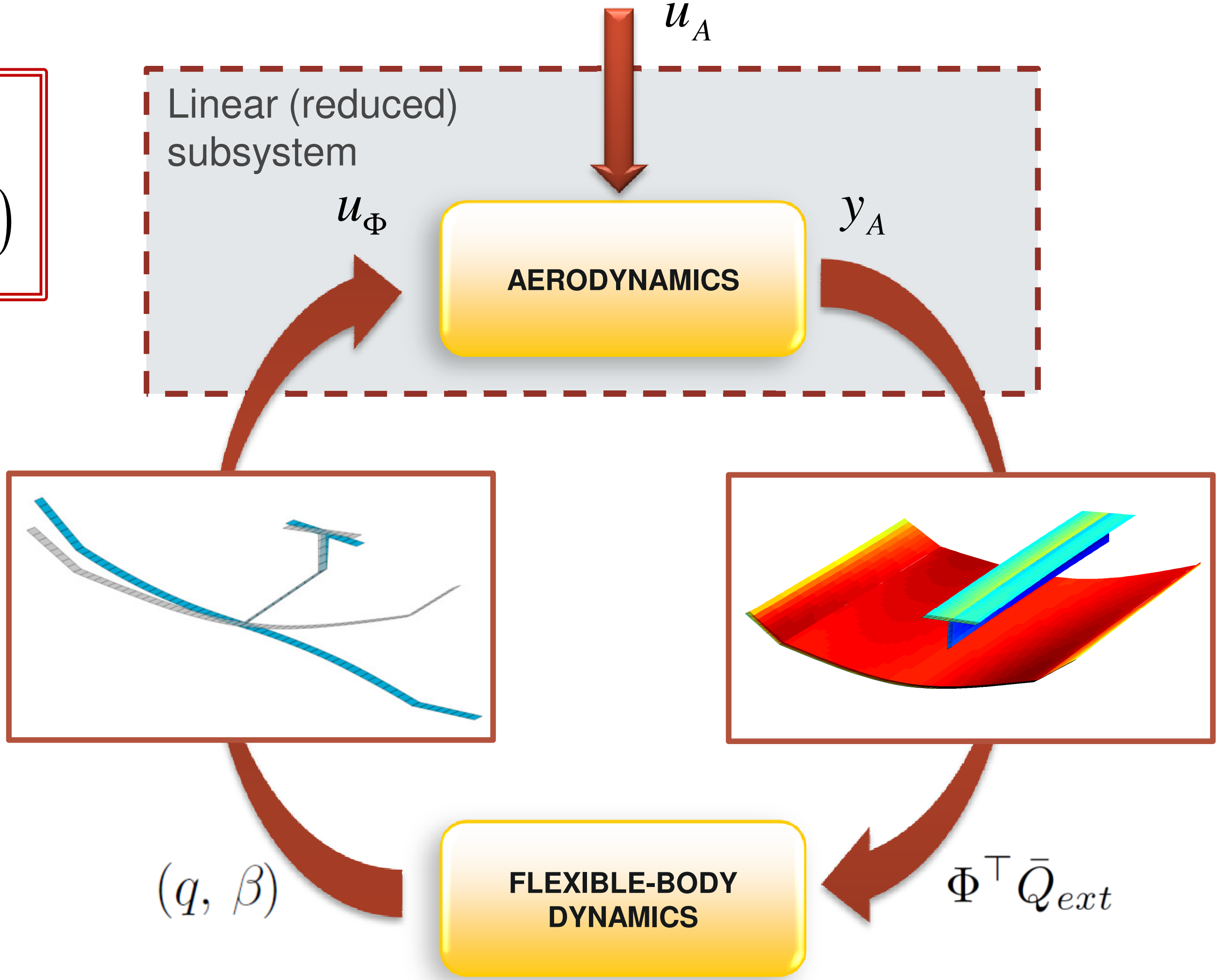

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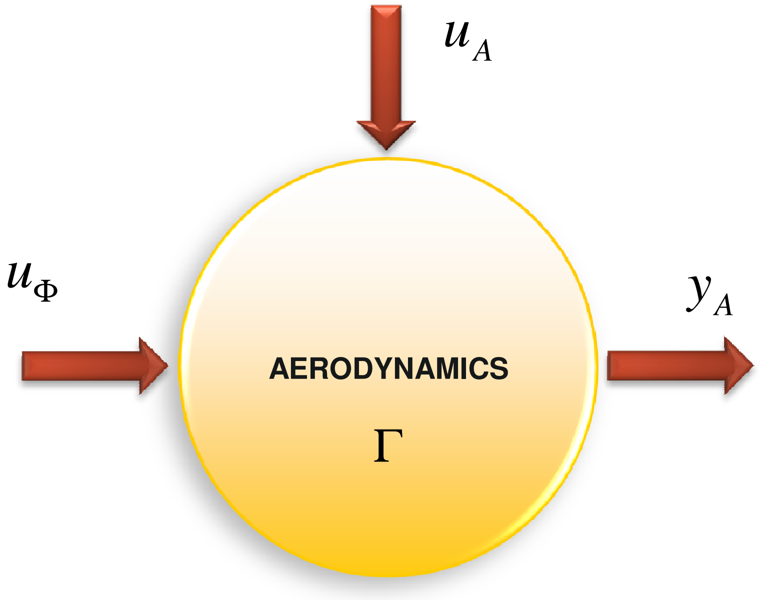
Balanced truncation of the aeroelastic system

- Large aerodynamic system ideal for balanced truncation
  - Few inputs and outputs transmitted by large system (10^4)



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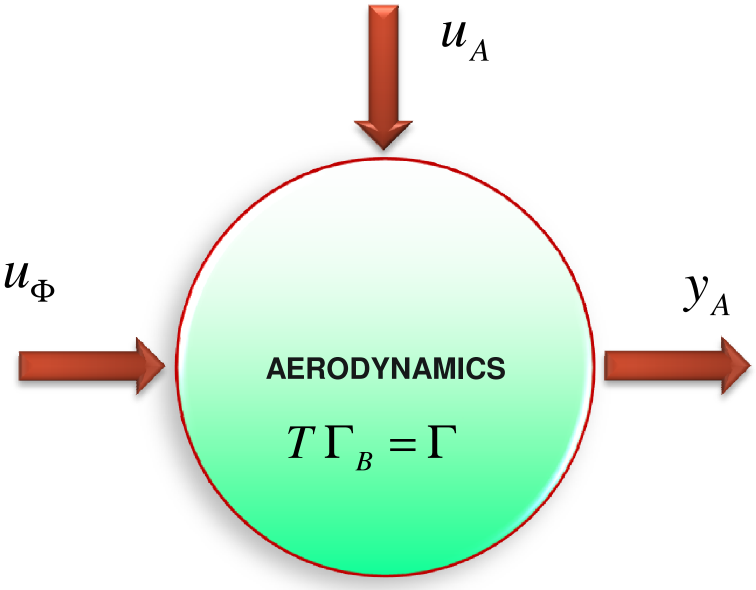
  - Balance aerodynamic states according to input and output energy (using controllability and observability Gramians)



$$\Delta\Gamma_B^{n+1} = T^{-1}AT\Delta\Gamma_B^n + T^{-1}B_S\Phi\Delta u_\Phi^n + T^{-1}B_A u_A^n$$
$$\Delta y_A^n = \Phi^T\left(CT\Delta\Gamma_B^n + D_S\Phi\Delta u_\Phi^n + D_A u_A^n\right)$$

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  - Few inputs and outputs transmitted by large system (10^4)
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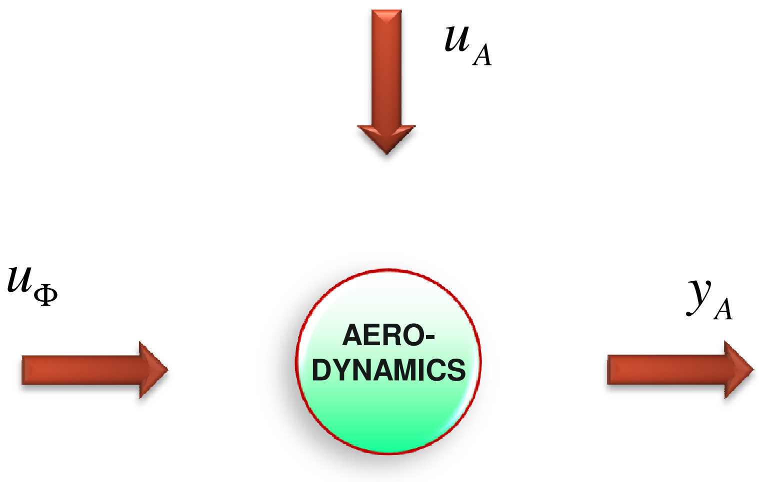
  - **Truncate least controllable and observable states**



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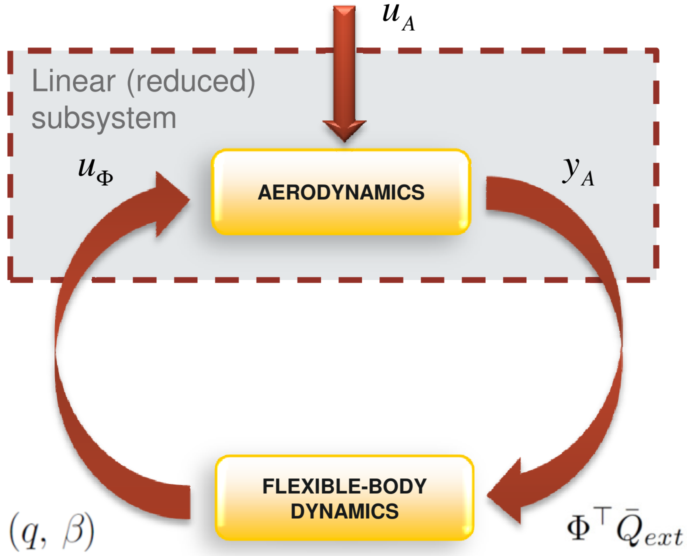
Aeroelastic system for aircraft analysis

1. Aeroelastic system for maneuvering flexible aircraft
   - Suitable for **large** rigid-body angular velocities with resulting coupling terms in the elastic deformations
   - Dynamic load calculations due to gust and **maneuver**, real-time simulations, optimisation, and control



2. Monolithic framework of the integrated aeroelasticity and flight dynamics
   - Control synthesis, stability analysis, and optimisation
   - Suitable for **clamped** problems or **linear** rigid-body motions

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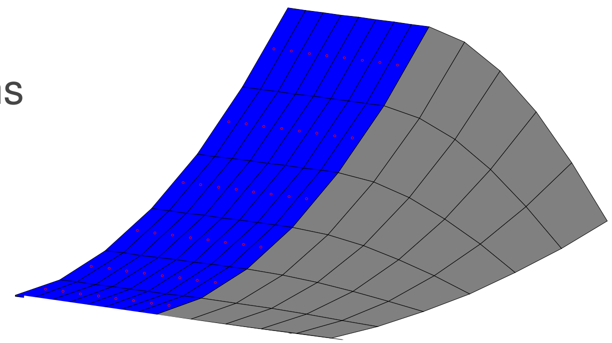

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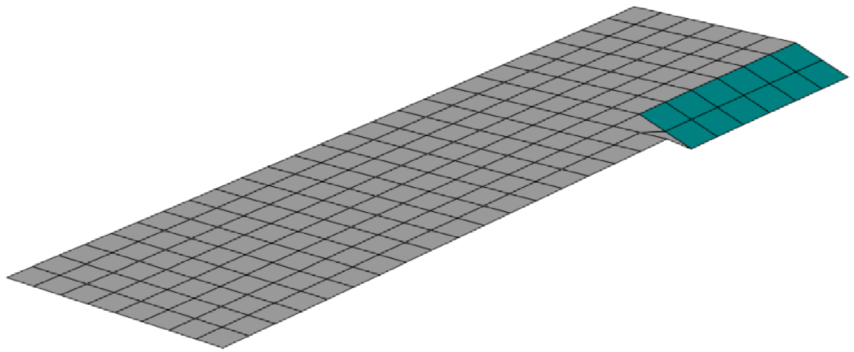
Numerical studies

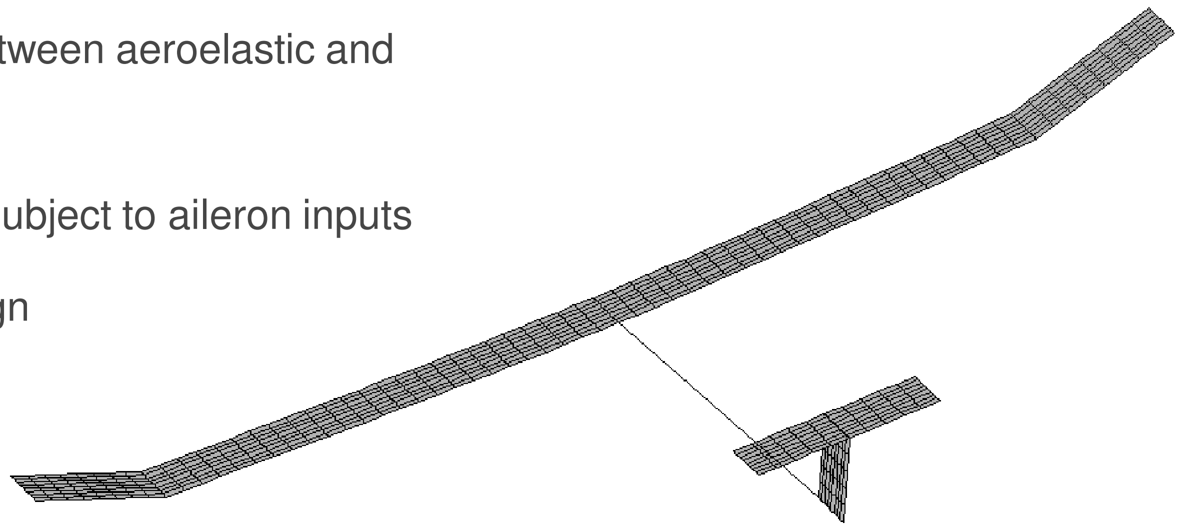
1. Goland wing with control surfaces



   - Verification of the linearized aeroelastic approach
   - Demonstration of balanced truncation on monolithic framework
   - Robust control synthesis based on ROM

2. Representative HALE aircraft

   - Insight into the coupling effects between aeroelastic and rigid-body modes
   - ROM of the maneuvering aircraft subject to aileron inputs
   - Generic approach for aircraft design

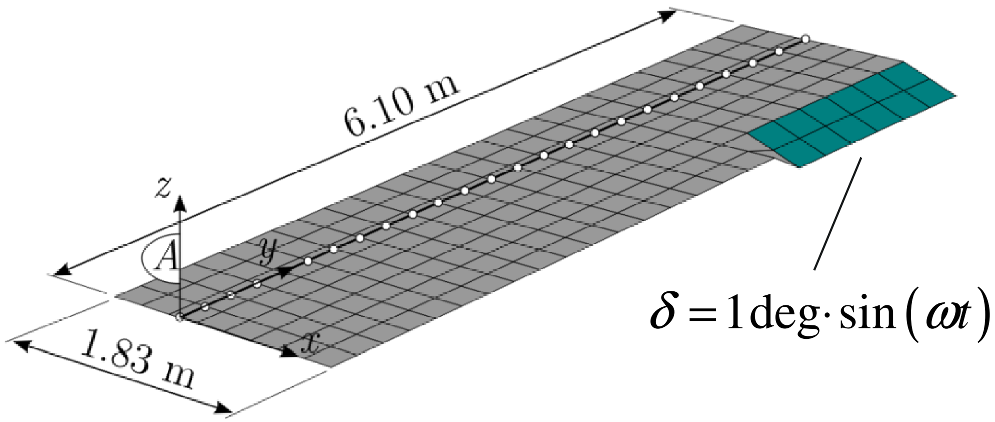


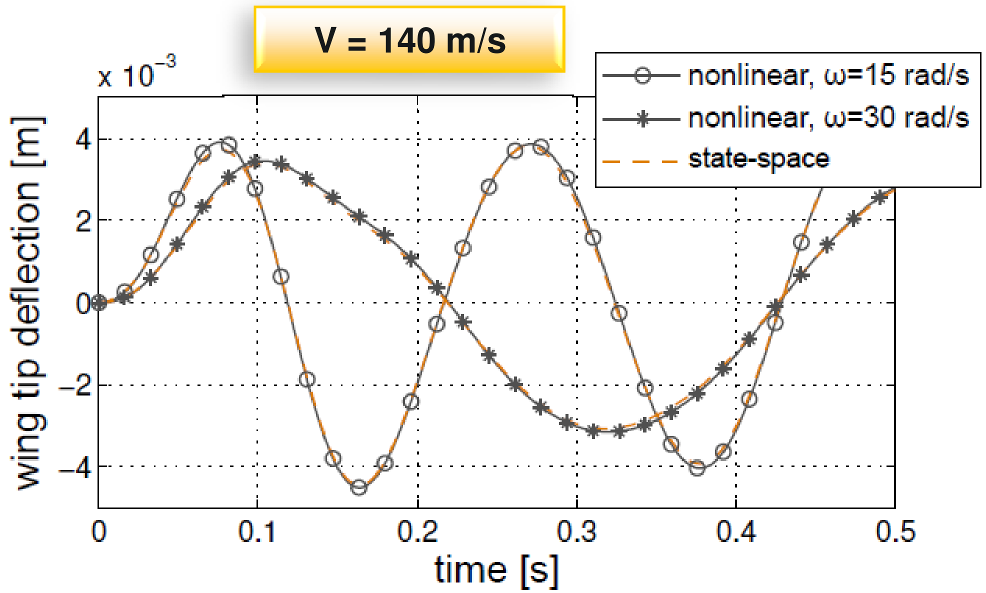
Goland wing

- Benchmark for aeroelastic calculations (Goland, 1945)
- Relatively stiff and low aspect-ratio wing
- Flutter speed using 16 x 26 bound panels (4550 states)
  - Present approach: V_f = 169 m/s ω_f = 70 rad/s
  - Murua et al. (2010): V_f = 165 m/s ω_f = 72 rad/s
  - Wang et al. (2006): V_f = 164 m/s -

Goland wing characteristics	
Aspect ratio	3.33
Elastic axis (from le)	33 %
Center of gravity (from le)	43 %
Mass per unit length	35.71 kg/m
Torsional rigidity	0.99×10^6 N·m²
Bending rigidity	9.77×10^6 N·m²

- Comparison with nonlinear time-marching solution





Hesse H, Palacios R, 2012. **Consistent Structural Linearisation in Flexible-Body Dynamics with Large Rigid-Body Motion**. *Computers and Structures* 110-111.

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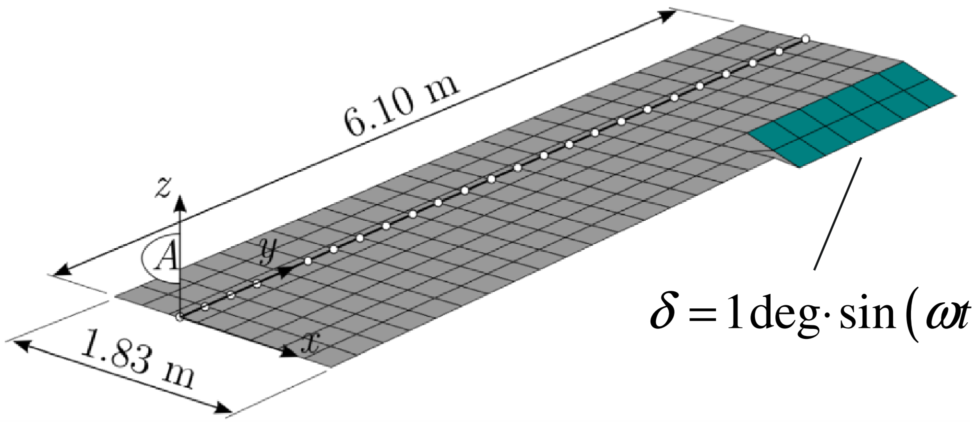
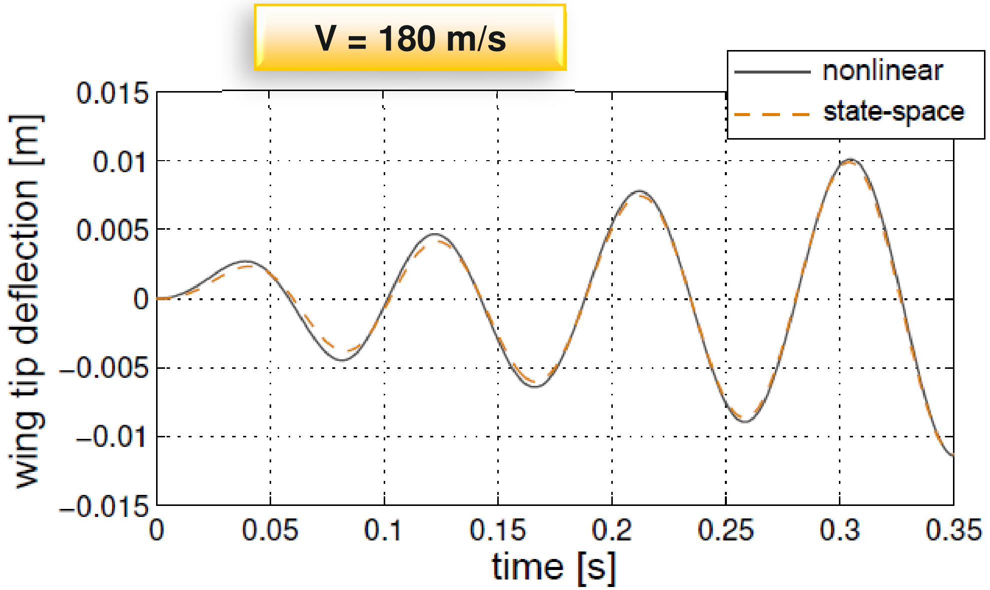
State-space system predicts high frequency aeroelastic response

<u>But:</u> large system size obstacle for effective aircraft design

- Comparison with nonlinear time-marching solution



$$\delta = 1\,\mathrm{deg}\cdot\sin(\omega t)$$



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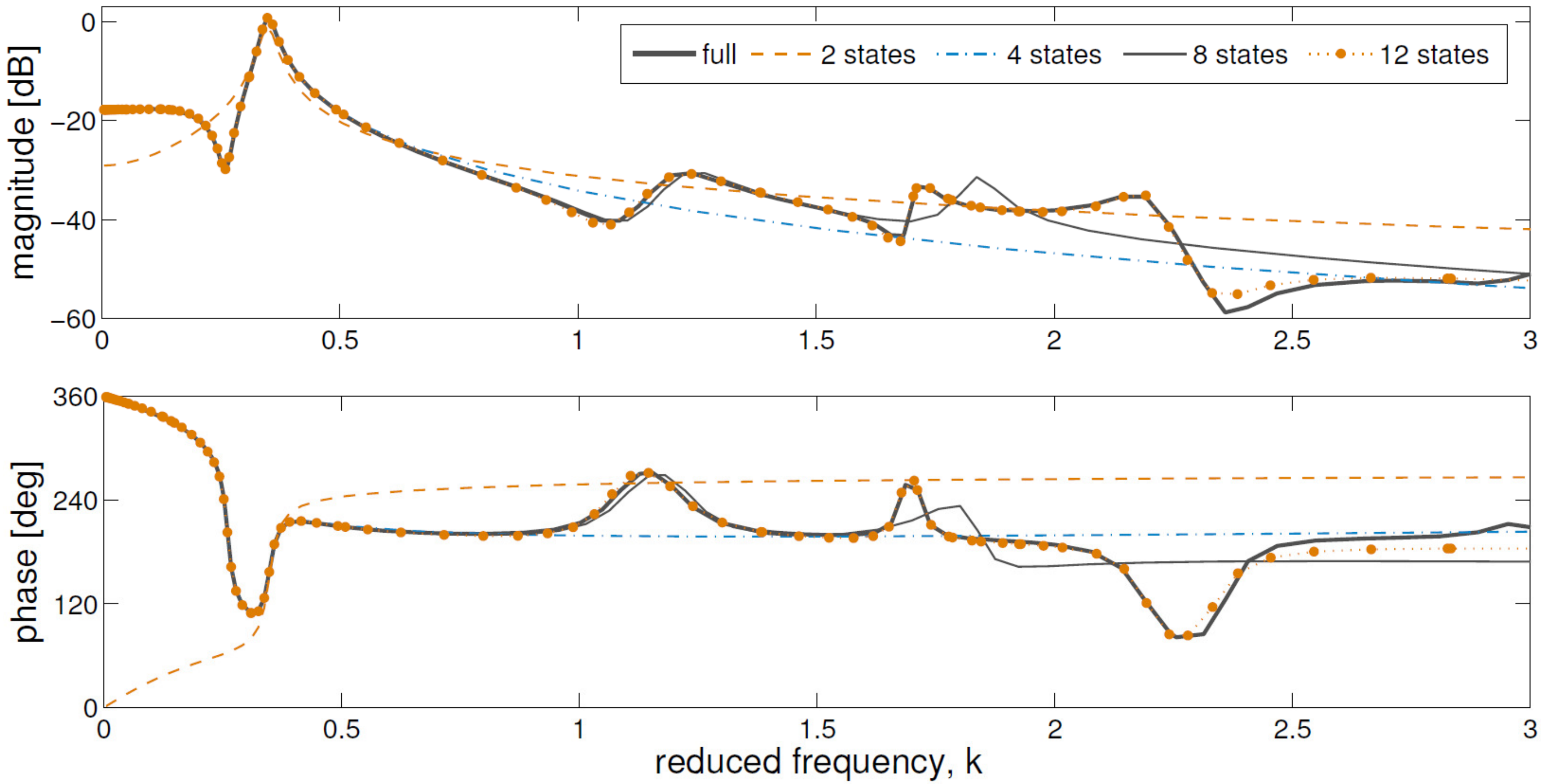
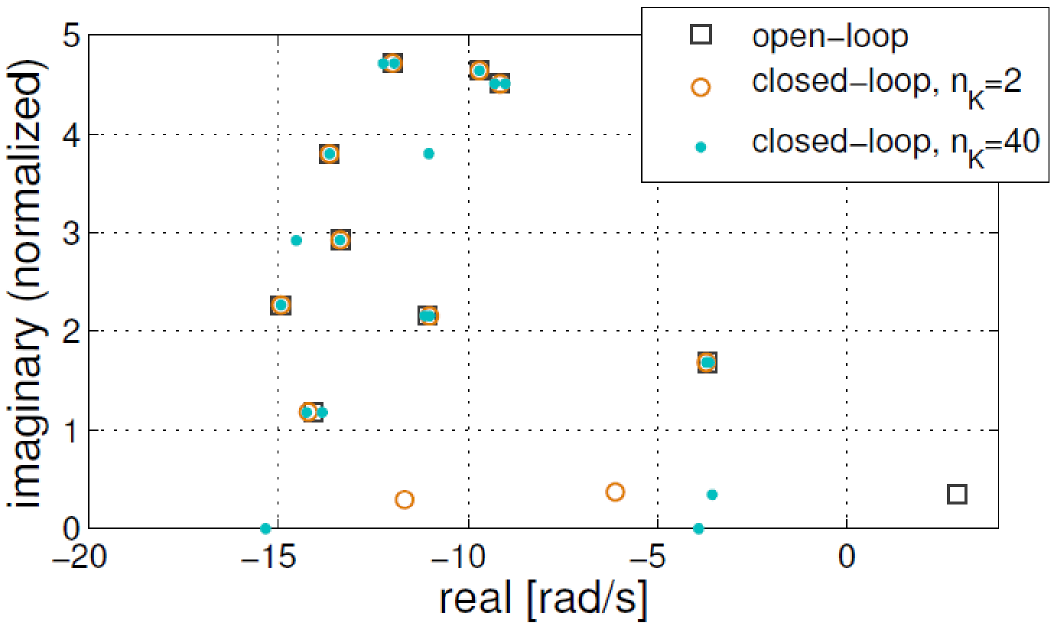
Model reduction for the Goland wing

- Balanced truncation of the SISO aeroelastic system at ***V* = 180 m/s** with 4550 states with aileron input and tip deflection as output



Control synthesis for the Goland wing

- Robust control synthesis using H_∞ for suppression of structural vibrations
- Demonstrate flutter suppression of the Goland wing at V=180 m/s



Model reduction enables use of higher fidelity tools to reduce uncertainties

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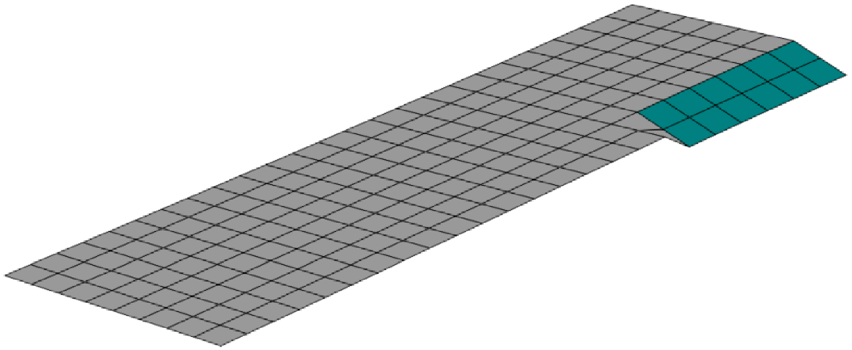

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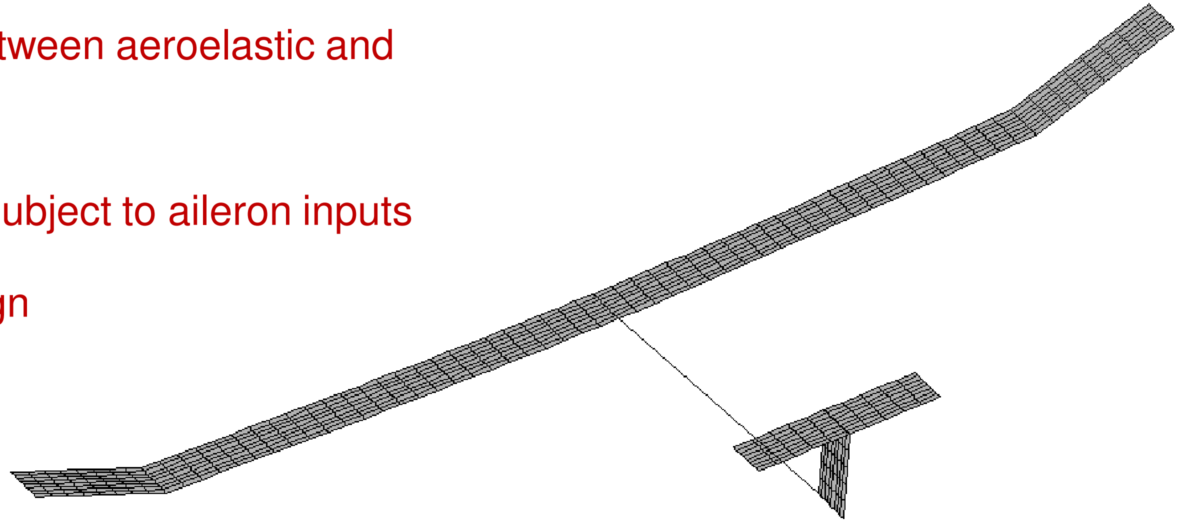
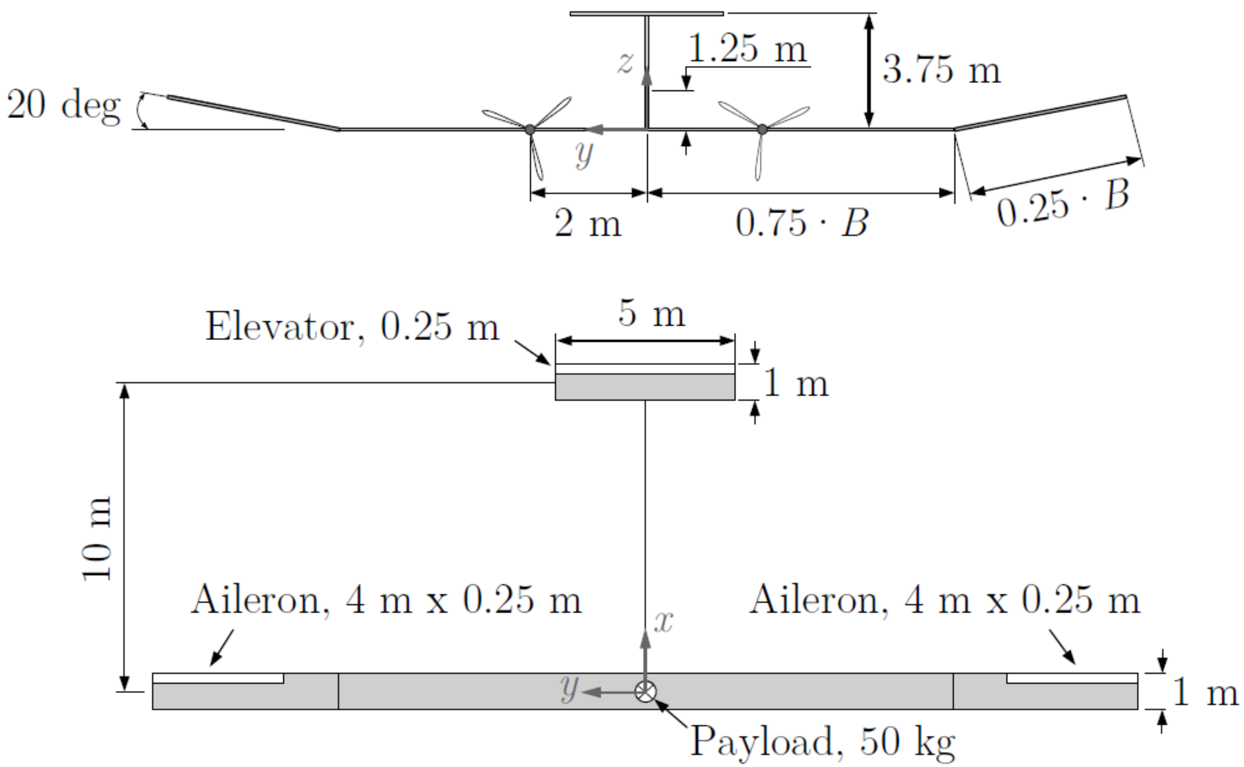


Representative HALE UAV

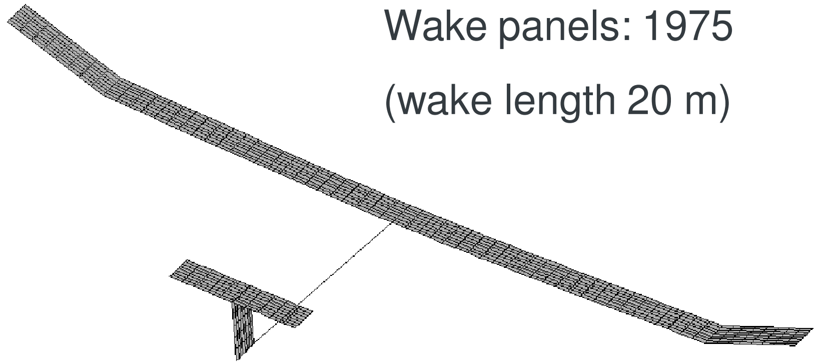


HALE model characteristics	
Aspect ratio	16
Elastic axis (from le)	50 %
Center of gravity (from le)	50 %
Mass per unit length	0.75 kg/m
Torsional rigidity	$1\sigma \times 10^4$ N·m^2
Bending rigidity	$2\sigma \times 10^4$ N·m^2

Bound panels: 632

Wake panels: 1975

(wake length 20 m)



Free-stream velocity: 30 m/s with time step 0.02 s

Flexible main wing

Rigid fuselage and T-tail

Murua J, Palacios R, Graham JMR, 2012. **Open-Loop Stability and Closed-Loop Gust Alleviation on Flexible Aircraft Including Wake Modeling**, AIAA 2012-1484.
Hesse H, Murua J, Palacios R, 2012. **Consistent Structural Linearisation in Flexible Aircraft Dynamics with Large Rigid-Body Motion**, AIAA 2012-1402.

Aeroelastic system for aircraft analysis

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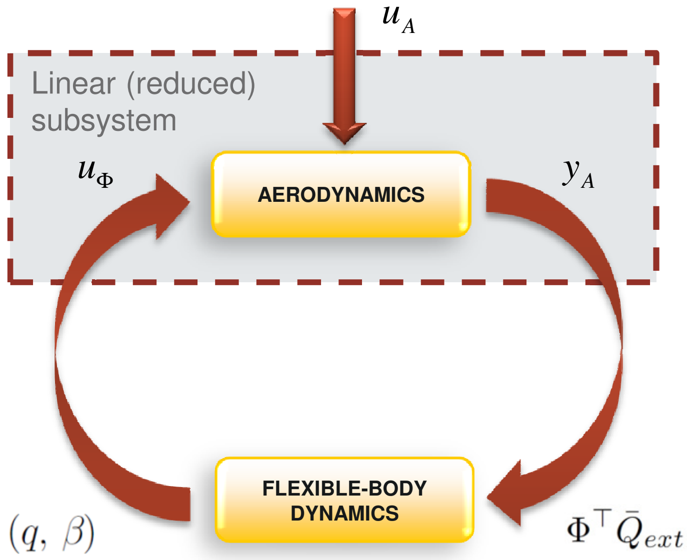

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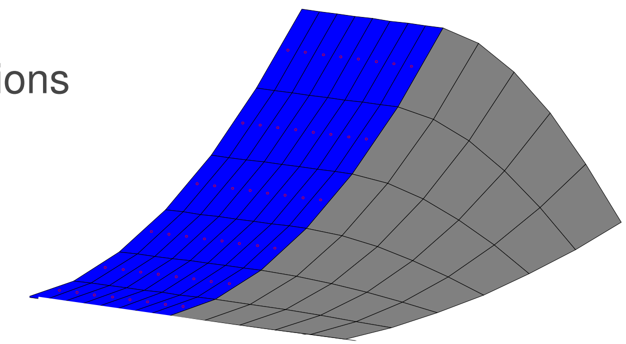

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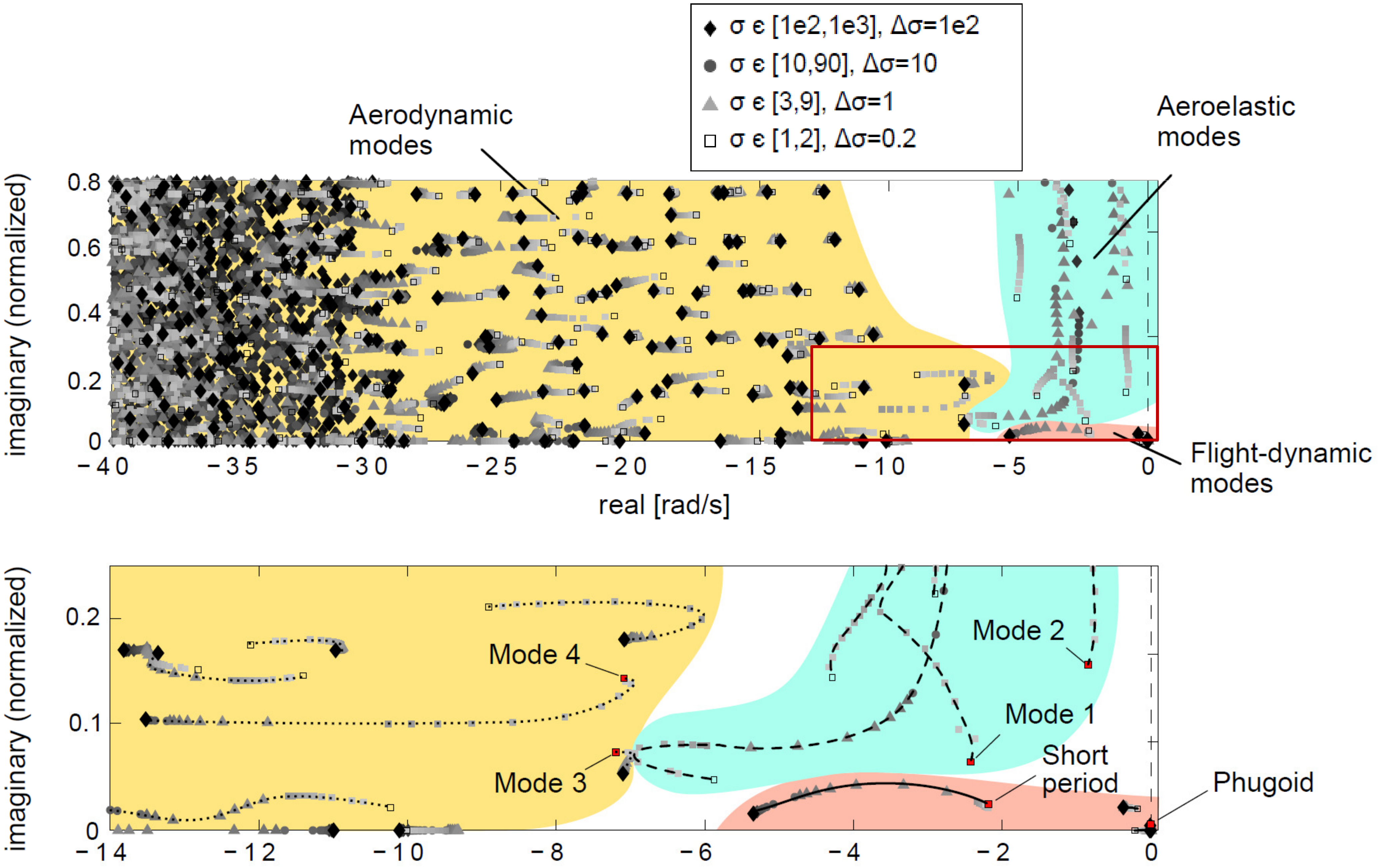
Coupled aeroelastic/flight dynamic stability



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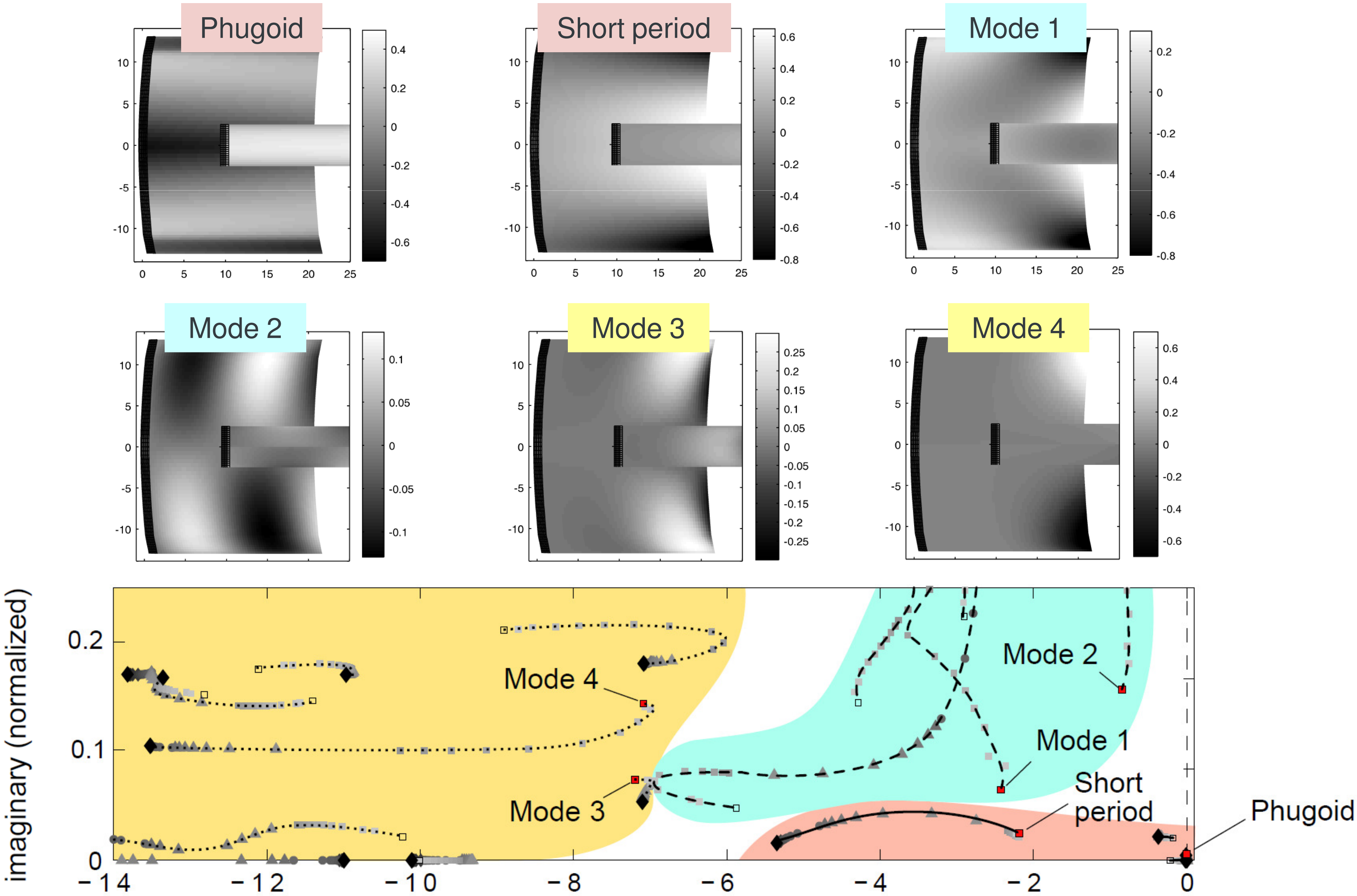
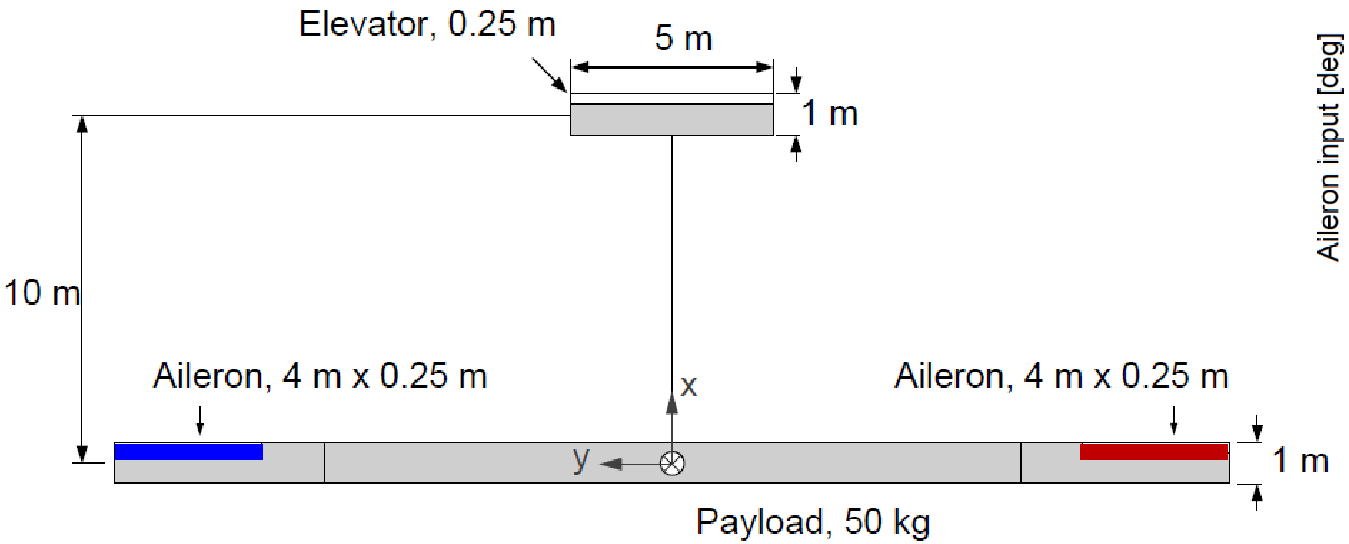
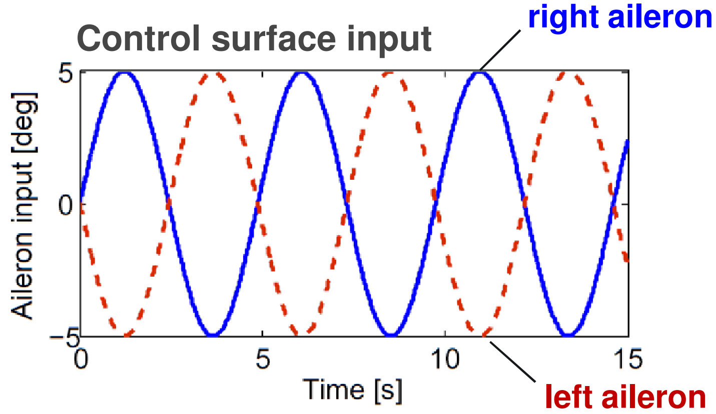
Aerodynamic part of modeshapes

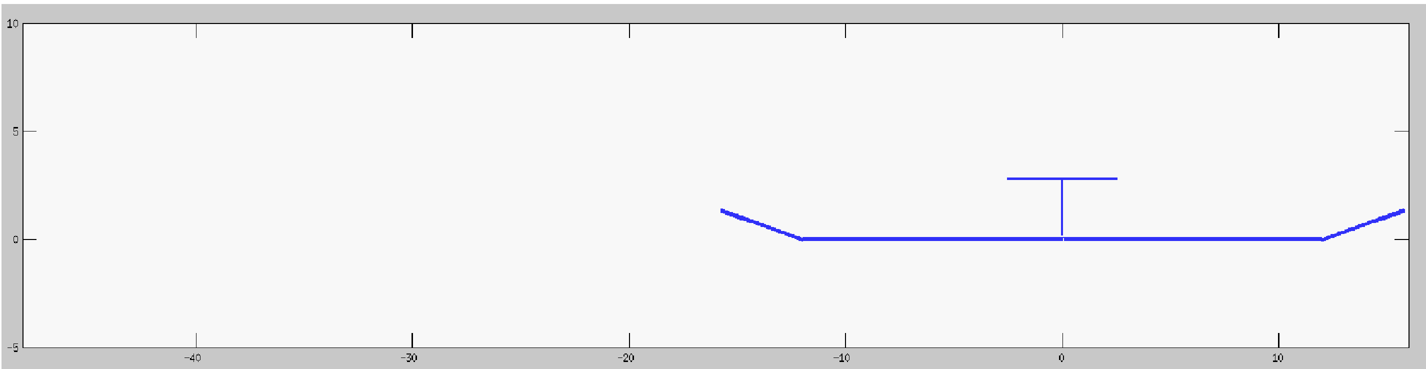


Open-loop response of maneuvering HALE UAV





Stiff configuration with σ = 1000



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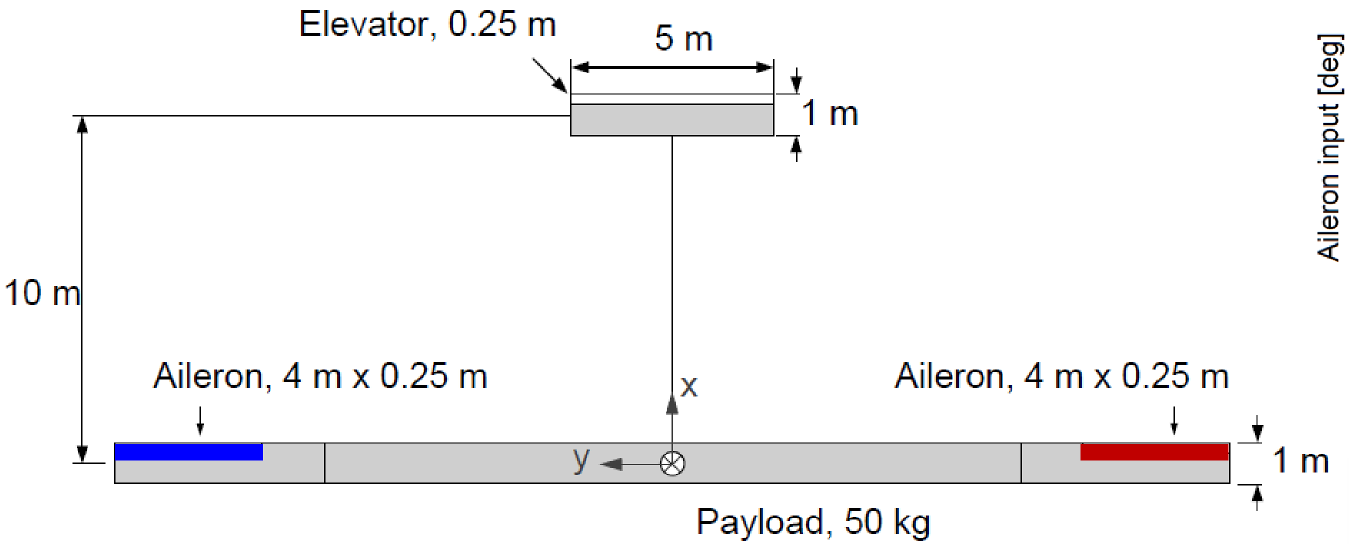
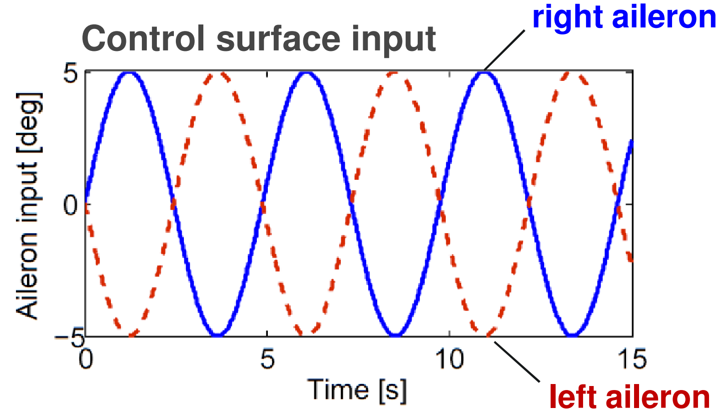


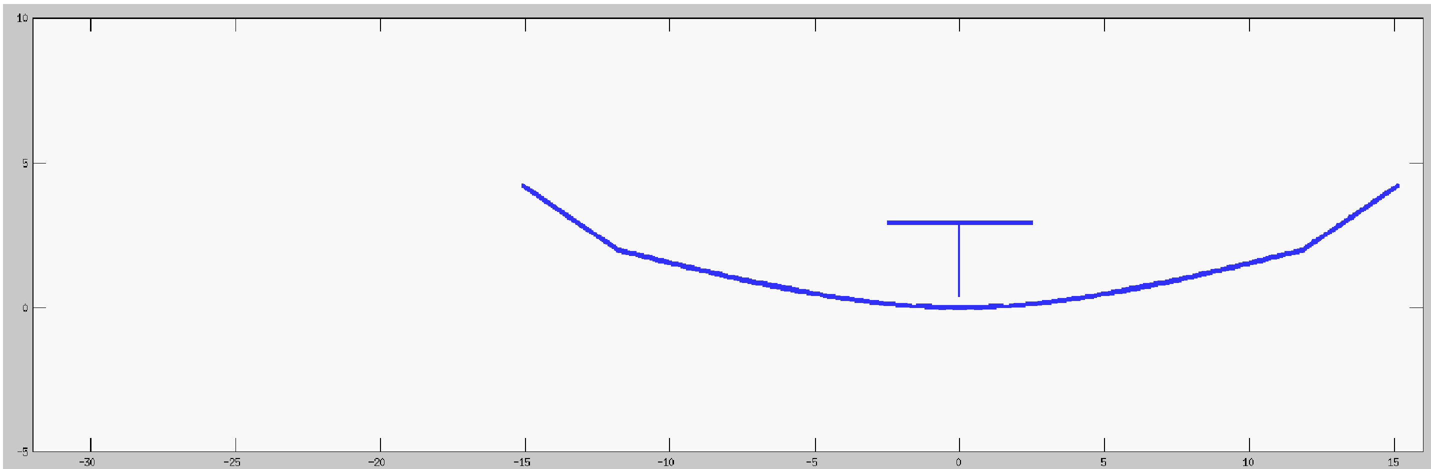


System size:

3239 aerodynamic states

1068 structural states

Flexible configuration with $\sigma = 2$



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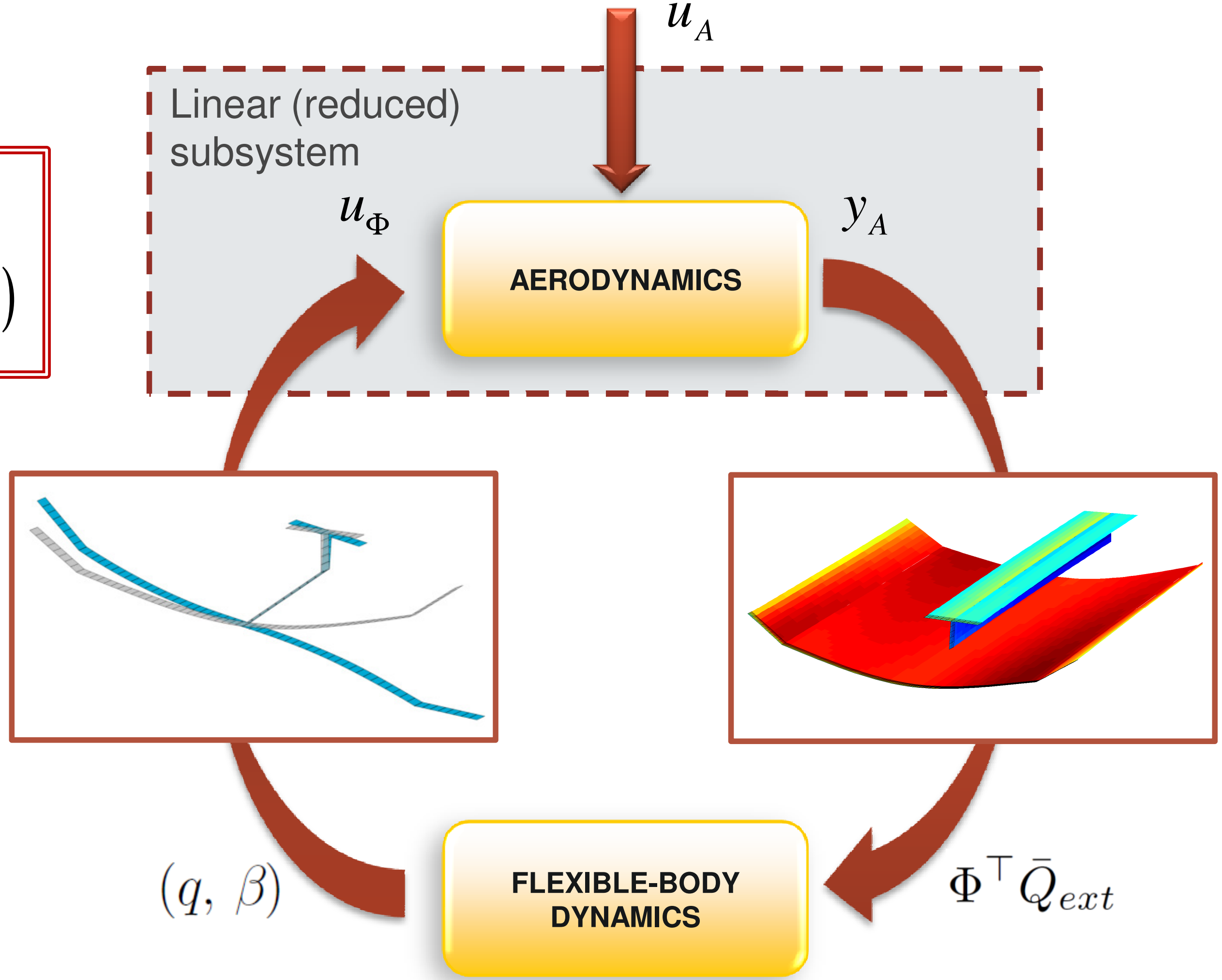

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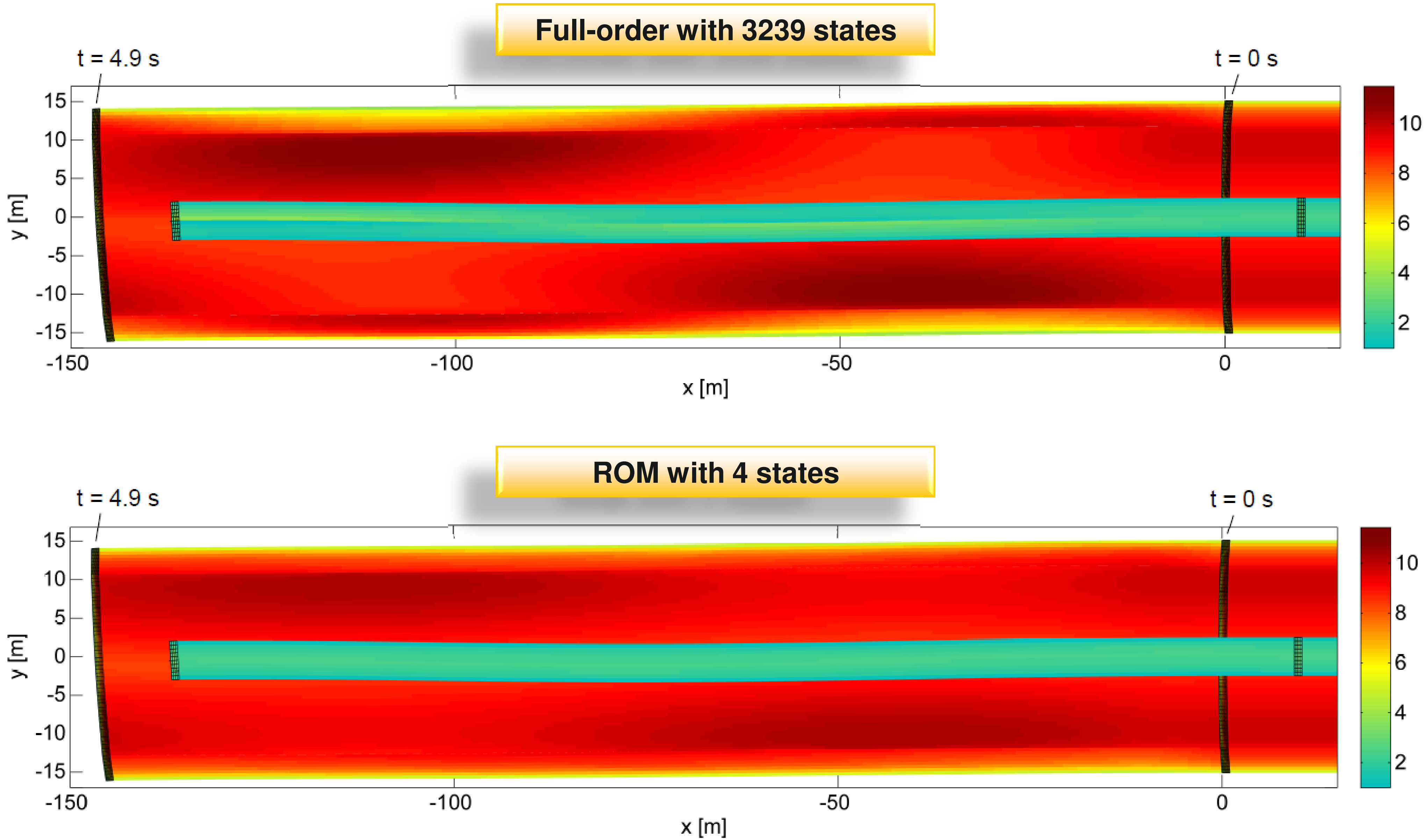
ROM response of maneuvering HALE UAV



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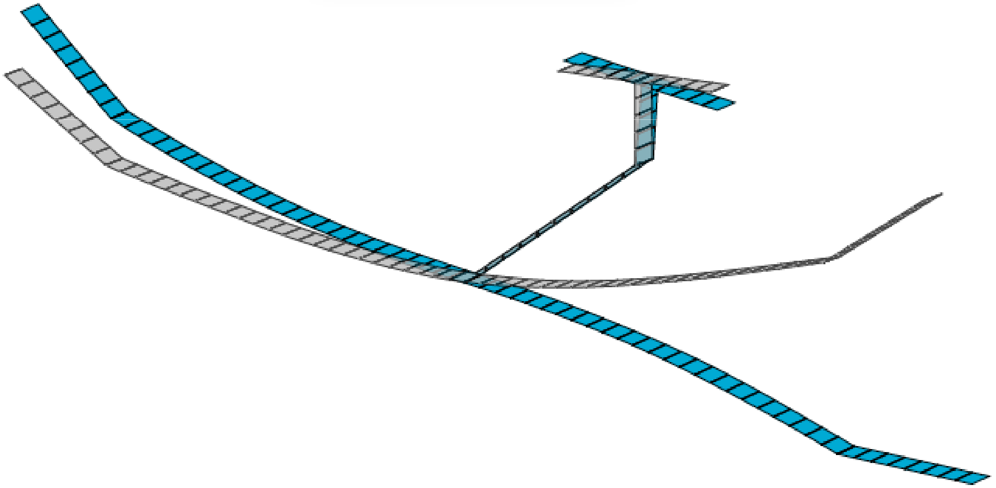
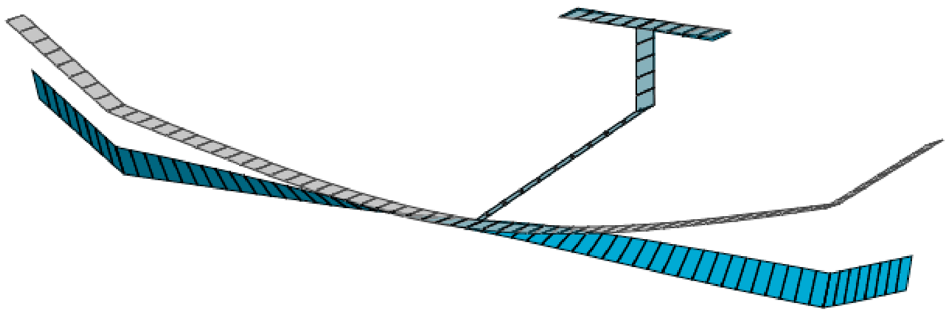
ROM response of maneuvering HALE UAV

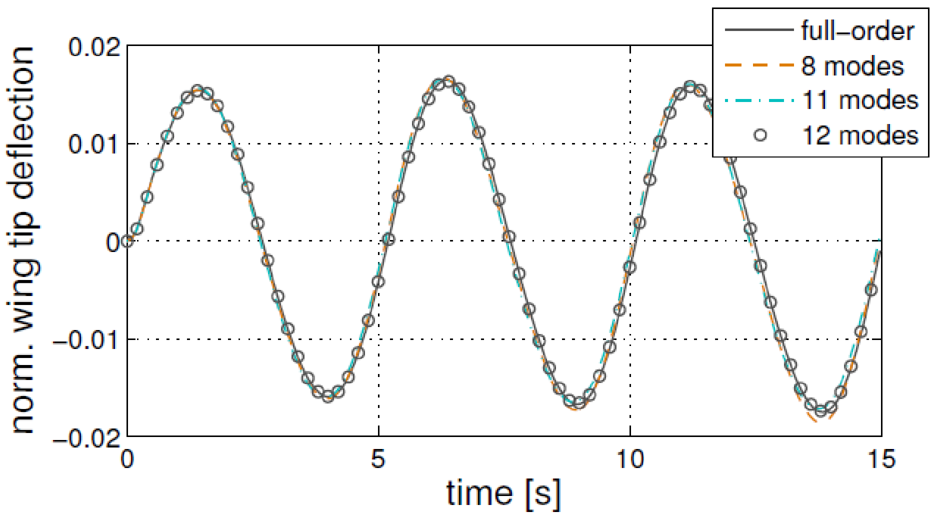
Mode 8

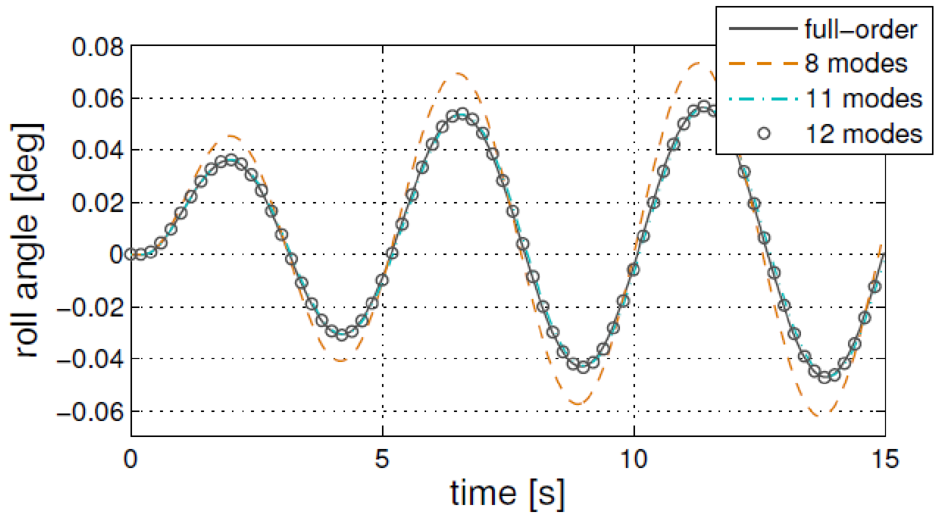
Mode 11





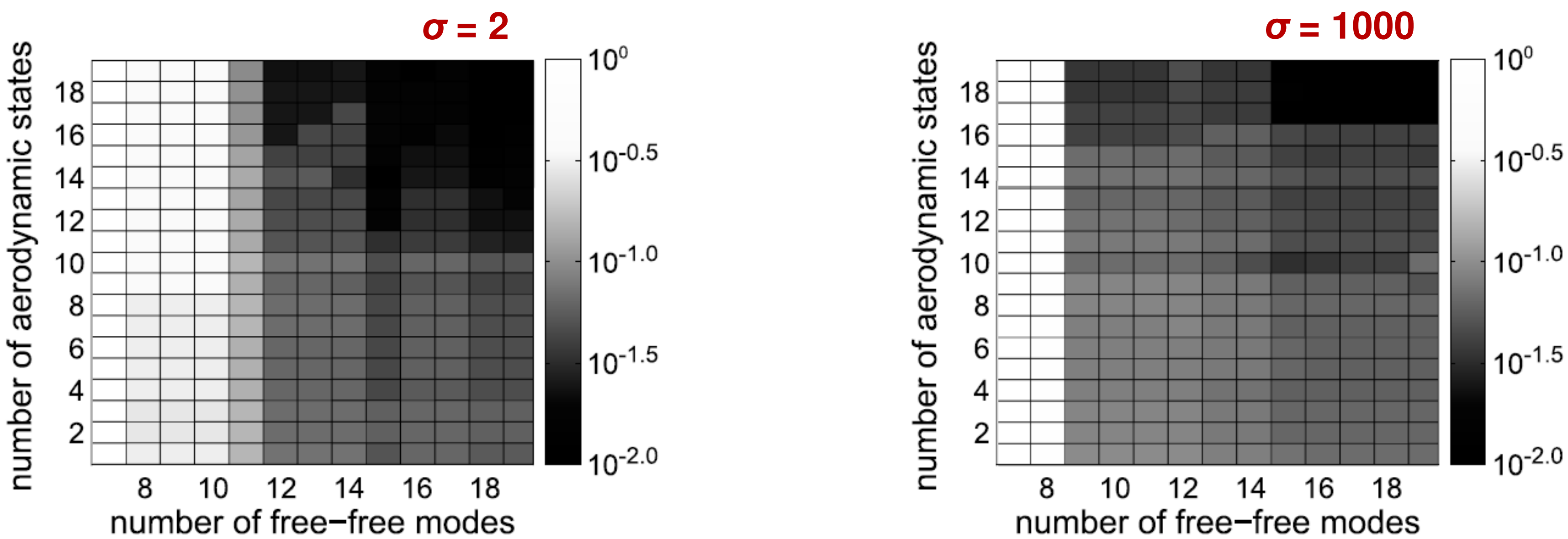
Reduce number of free-free modes





Generic approach?

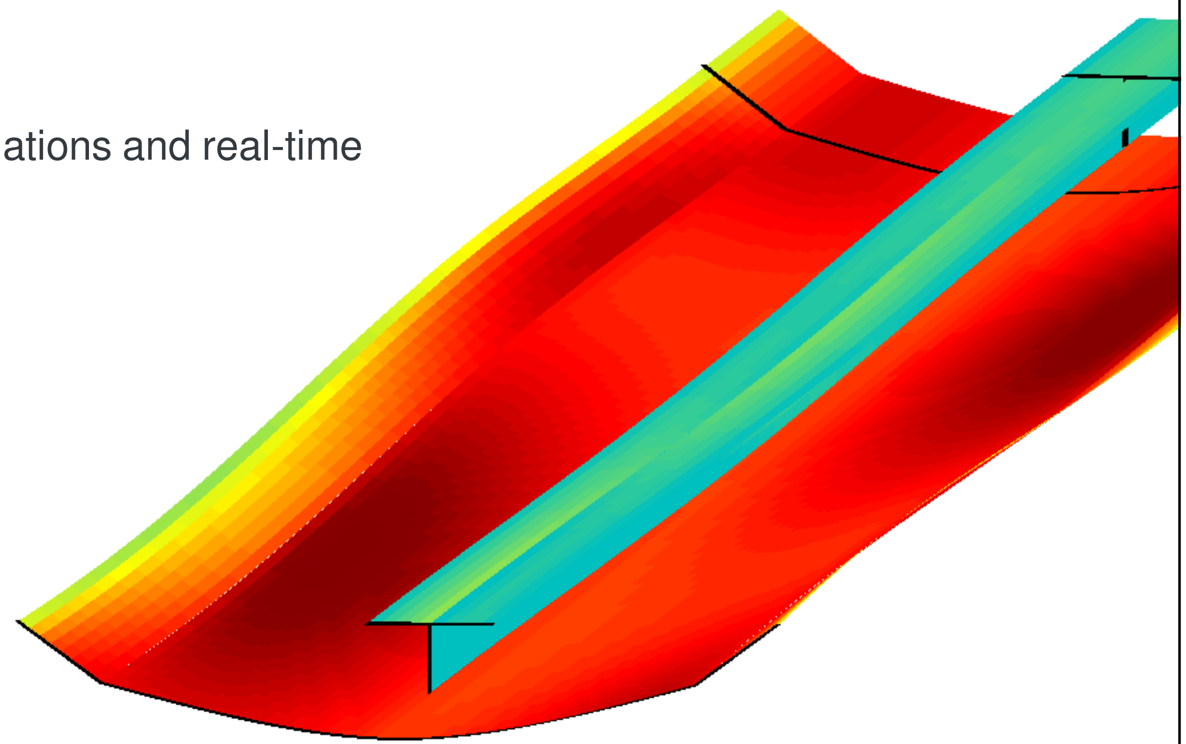
- $L\infty$ error norm of flight dynamic response
  - ➢ Aeroelastic framework allows automatic exploration of ROM
  - ➢ Inclusion of unnecessary elastic modes harms the balanced truncation of the aerodynamic system
  - ➢ Generic approach for range of parameters, e.g. stiffness and flight speed



Model reduction by three orders of magnitude!

Concluding remarks

- ROM of an integrated framework for the analysis of very efficient aircraft in time domain
- Approach provides an alternative to frequency-based methods at a similar system size, but:
  - large trim deformations
  - includes coupling effects between aeroelastic and rigid-body dynamics response
  - captures the unsteadiness of the 3D flow
- Ideal for robust control synthesis, load calculations and real-time simulations of next-generation aircraft
  - Goland wing
  - Representative HALE aircraft



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Model Reduction in Flexible-Aircraft Dynamics with Large Rigid-Body Motion

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