DLR Pazy Wing Simulations for the 3rd Aeroelastic Prediction Workshop

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Theoretical Fundamentals: UVLM

- Basic VLM equation is solved for Γ

$$AIC \cdot \Gamma = RHS$$

- The right hand side sums all velocities

$$RHS = -\left(v_{rb} + v_{wake} + v_{gust} + v_{elastic}\right) \cdot n$$

- Wake shedding procedure accounts for Kelvin's theorem

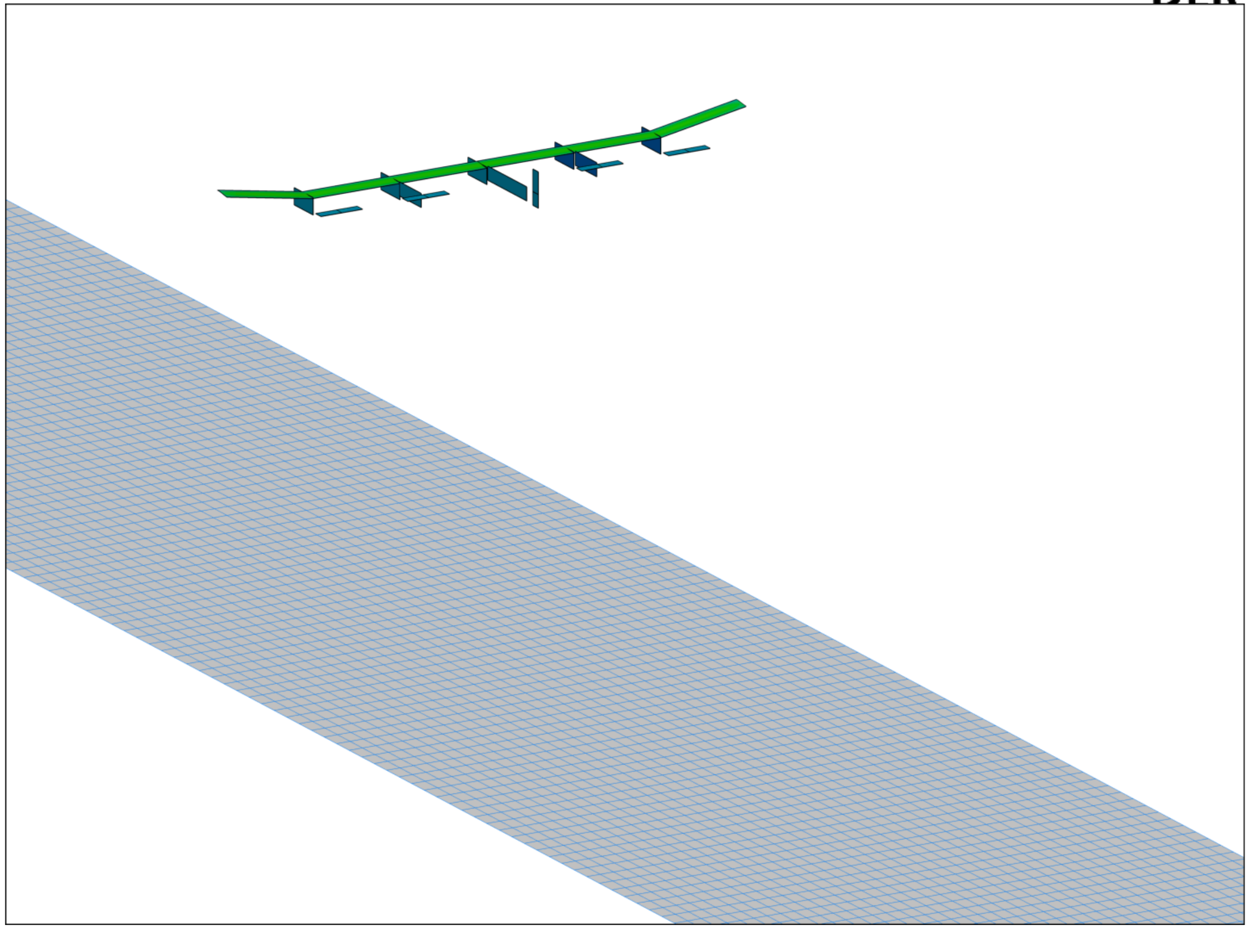
$$\frac{D\Gamma}{Dt} = \frac{1}{\Delta t}\left(\Gamma_{airfoil} + \Gamma_{wake}\right) = 0$$

- Unsteady forces from temporal derivative of circulation

$$F_u = \rho_\infty A_p \frac{\partial \Gamma}{\partial t} n$$

- Steady and quasi-steady forces from *effective* circulation

$$F_s = \rho_\infty \Gamma_{eff}\left(v_{rb} + v_{gust} + v_{elastic}\right) \times r$$



Linearized Formulation and Stability Analysis

- Derivation of a time-discrete state space model for the aerodynamic forces (which become a function of the circulation of the wake panels) and the structural dynamics, see Jonathan's Master Thesis (on LDWG Teamsite)
- Integration of both models into a monolithic aeroelastic state-space model

Aerodynamic model: $\Gamma_w^{k+1} = {}^aA\ \Gamma_w^k + [\ {}^aB_1 \quad {}^aB_2] \begin{Bmatrix} n \\ v_{el} \end{Bmatrix}^k$

Structural model: $\begin{Bmatrix} q_i \\ \dot{q}_i \end{Bmatrix}^{k+1} = {}^s\bar{A} \cdot \begin{Bmatrix} q_i \\ \dot{q}_i \end{Bmatrix}^k + {}^s\bar{B} \cdot \{\ {}^sf\}^k$

- Monolithic aeroelastic state space model in discrete time (no input vector here)

$$\rightarrow \begin{Bmatrix} \Gamma_w \\ q_i \\ \dot{q}_i \\ \ddot{q}_i \end{Bmatrix}^{k+1} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & 0 \\ A_{21} & A_{22} & A_{23} & \dots \cdot \varphi_i \\ A_{31} & A_{32} & A_{33} & \dots \cdot \varphi_i \\ \frac{A_{31}}{\Delta t} & \frac{A_{32}}{\Delta t} & \frac{A_{33}-I}{\Delta t} & 0 \end{bmatrix} \cdot \begin{Bmatrix} \Gamma_w \\ q_i \\ \dot{q}_i \\ \ddot{q}_i \end{Bmatrix}^k$$

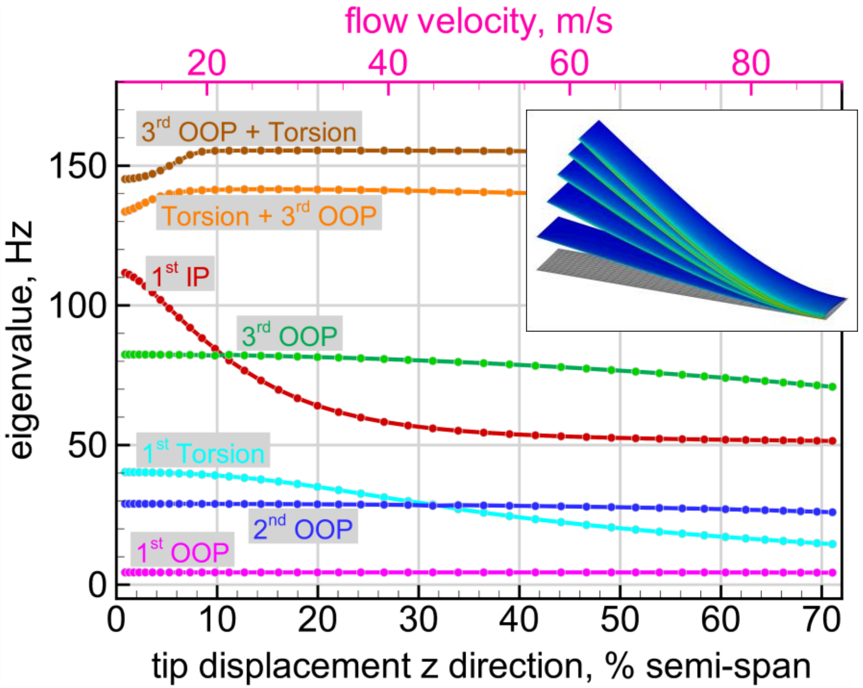
- Eigenvalue Analysis on Dynamics Matrix of entire aeroelastic system (*p-method*)

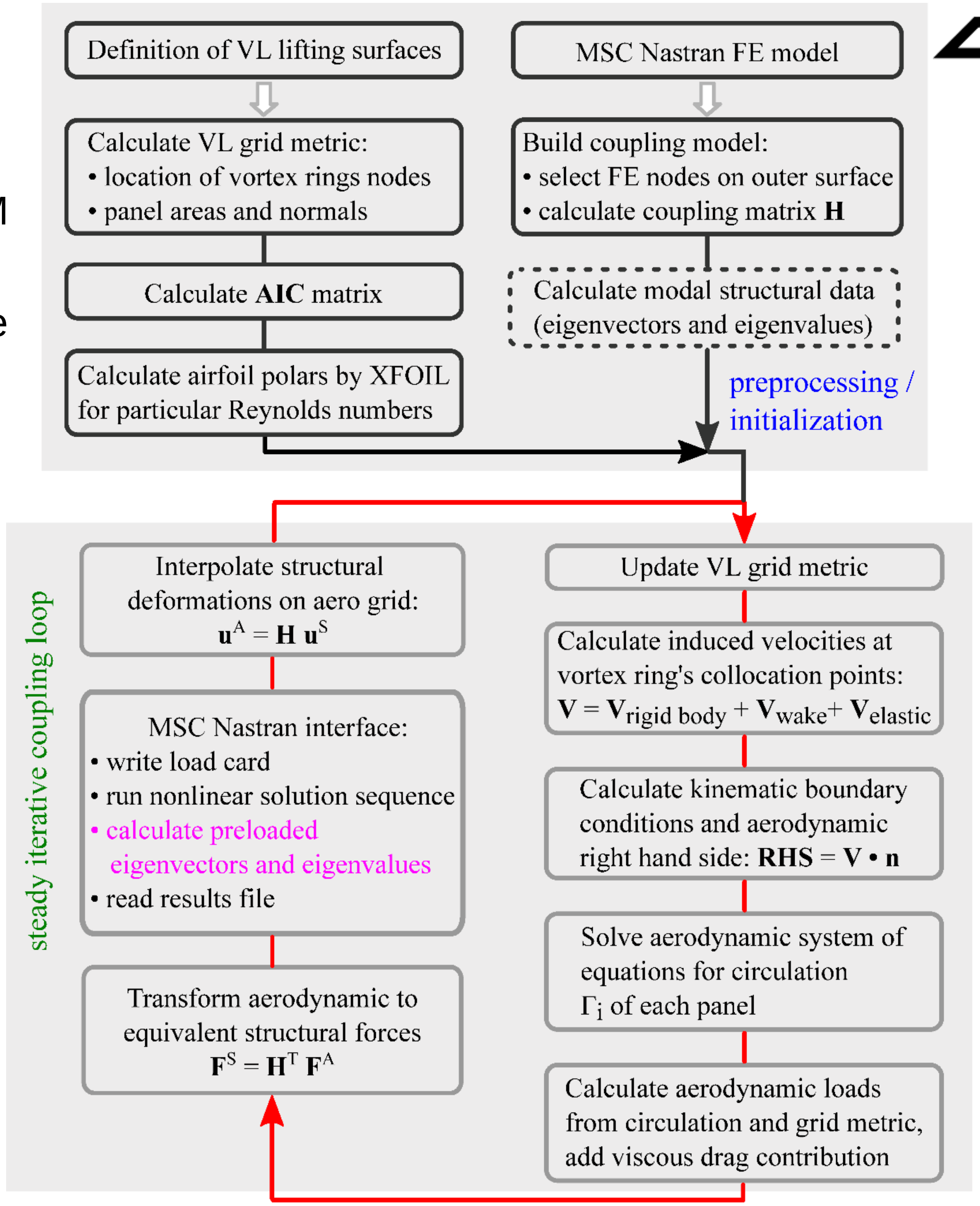
→ Eigenvalues in time discrete form $\boldsymbol{z_i}$, transformation into time continuous form, $\boldsymbol{\lambda_i}$

  - Stability criterion: $\boldsymbol{Re}\ (\boldsymbol{\lambda_i}) \leq \boldsymbol{0}$
  - $\boldsymbol{Re}\ (\boldsymbol{\lambda_i})$ → Damping
  - $\boldsymbol{Im}\ (\boldsymbol{\lambda_i})$ → Frequency

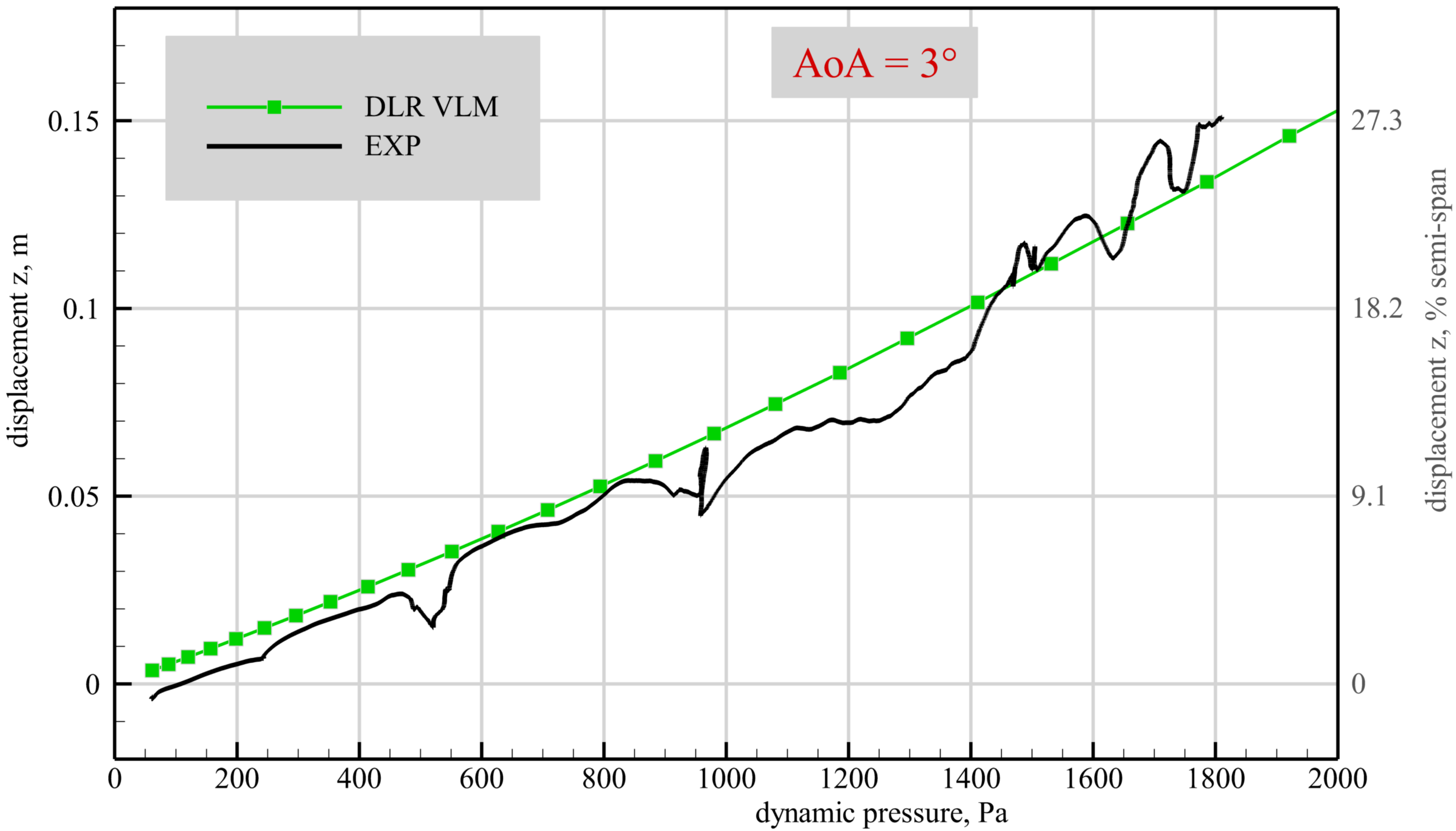
Static Coupling Simulations

- Static coupling simulations using a vortex-ring, zero-order VLM coupled spatially to Nastran SOL400 in the loop (with GFEM)
- Aeroelastic stability analysis is to be done about states of large deflections, so we need pre-loaded mode shapes
- Normal modes analysis: $(K - \omega^2 M)\varphi = 0$
  - on <u>deformed</u> structure: $\left(K^{(t)} - \omega^2 M\right)\varphi = 0$





Static Coupling Simulations



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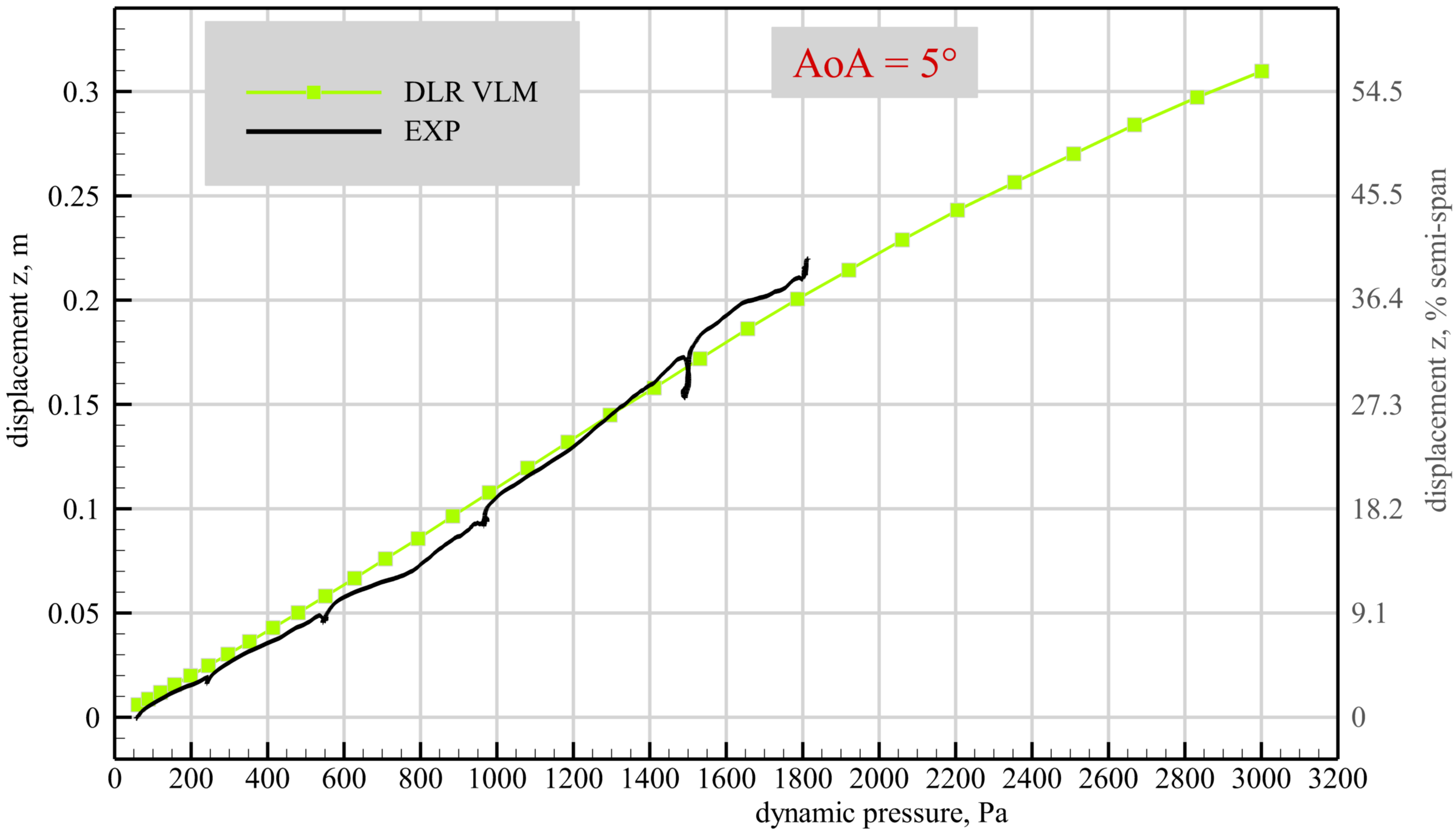
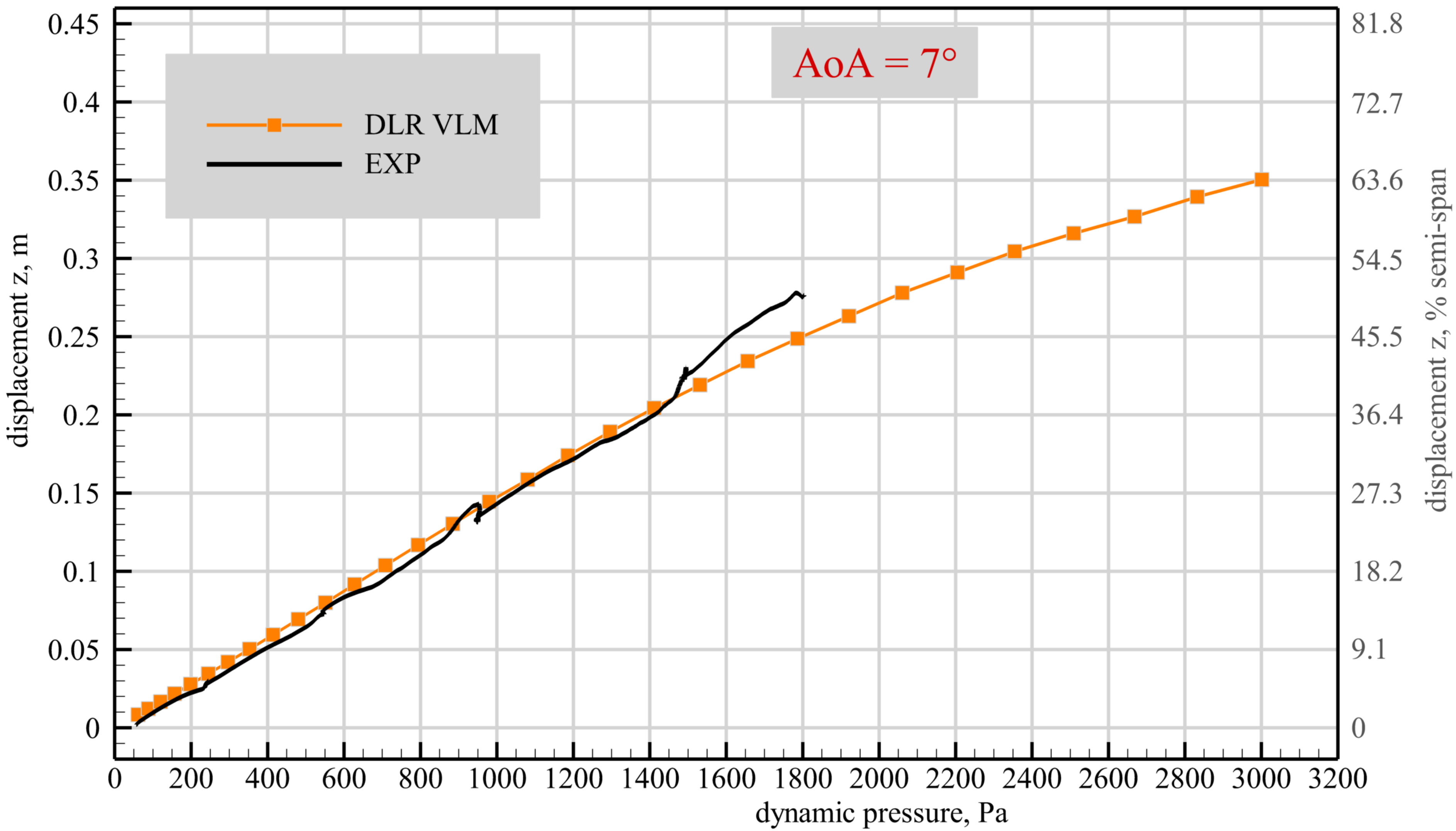
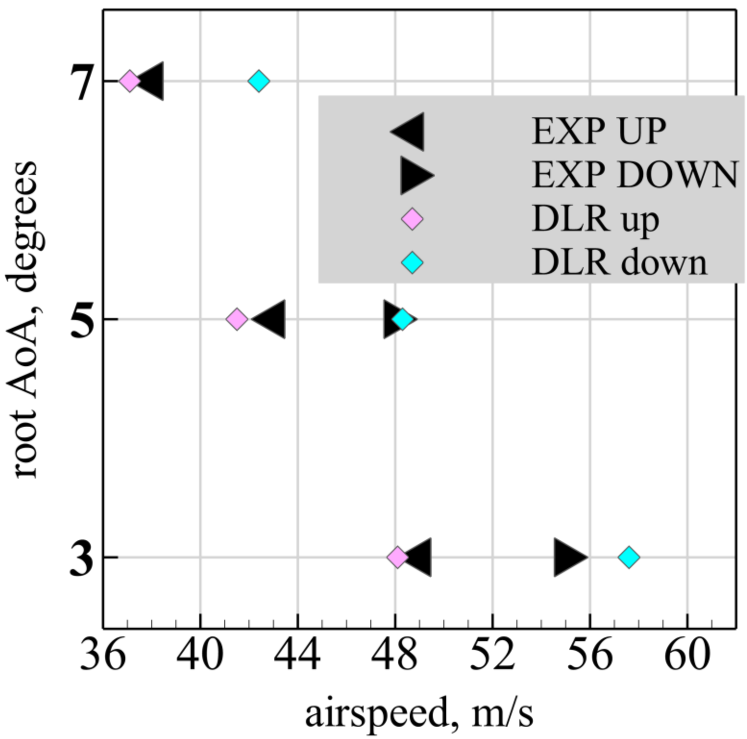


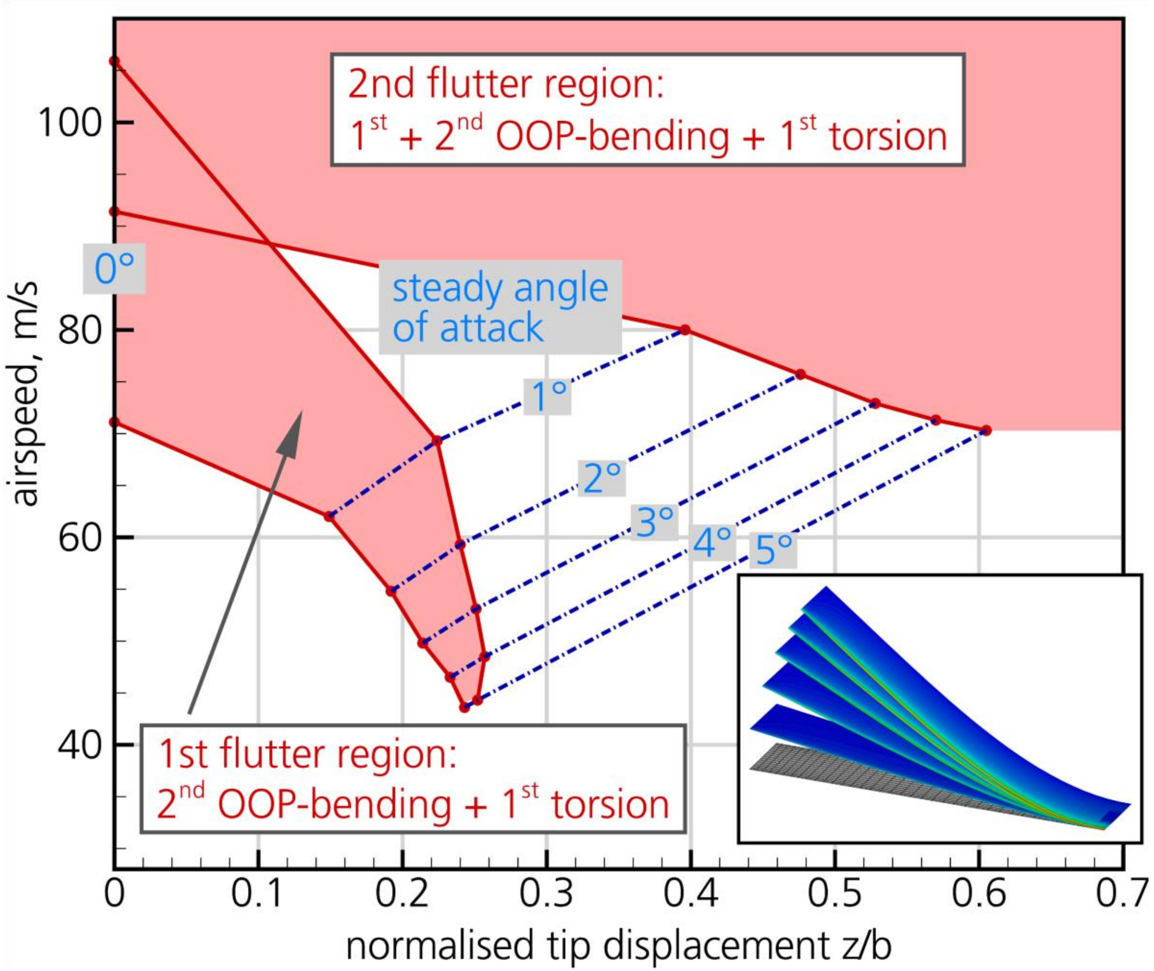
Static Coupling Simulations



Dynamic Stability boundaries

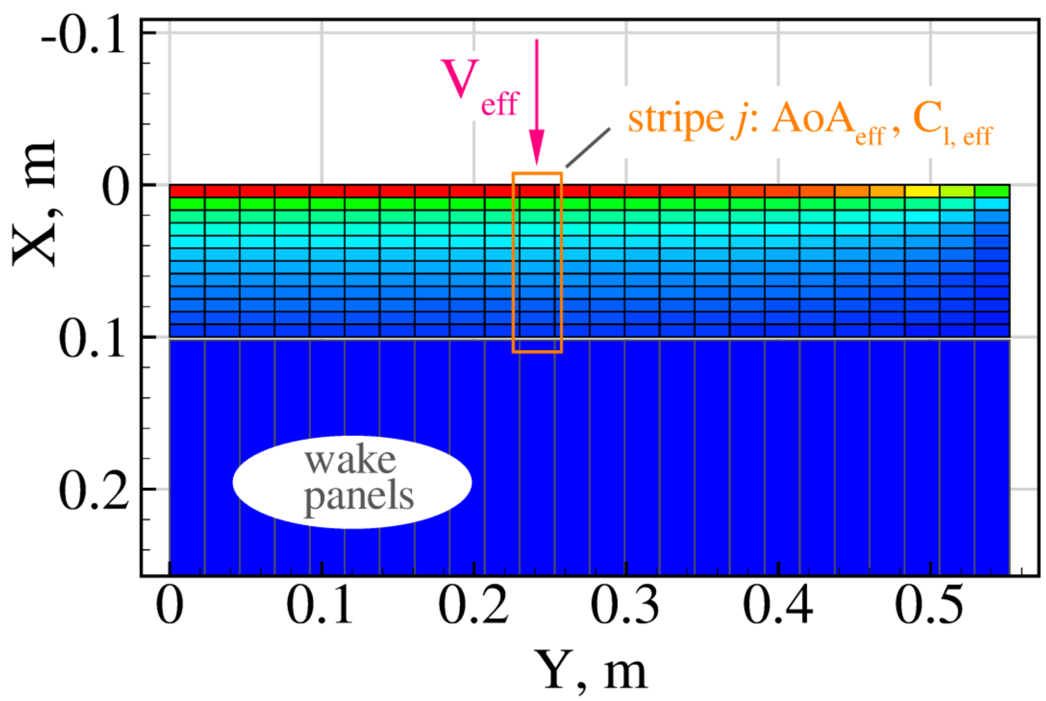
DLR

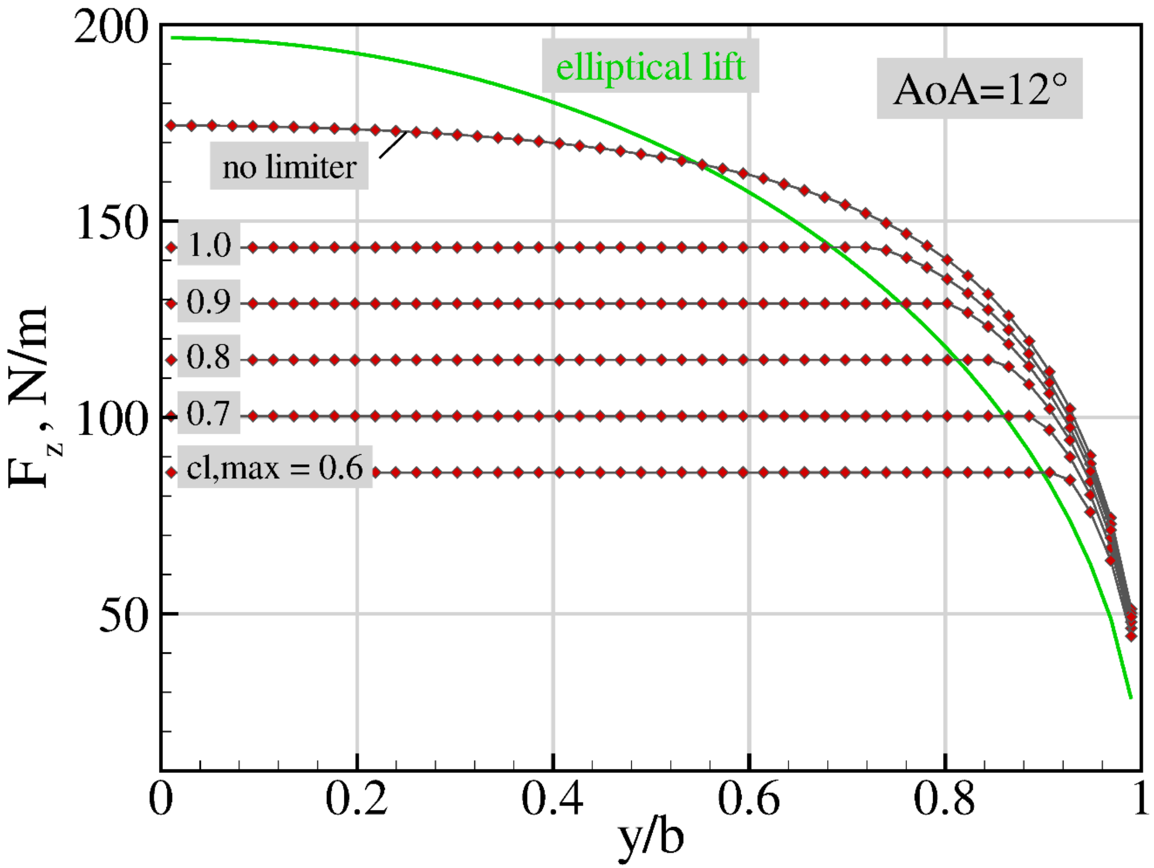




Extensions to account for aerodynamic nonlinearities (stall)

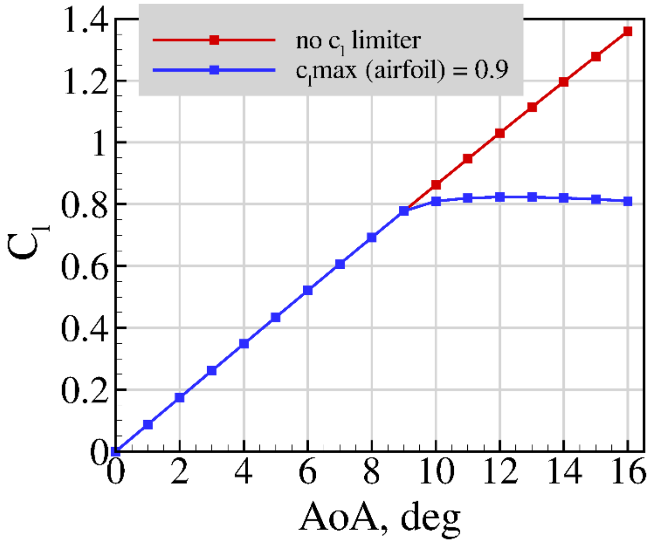
- Determine the effective lift coefficient of each stripe
- Reduce circulation of aero panels to match user-defined maximum lift coefficient of stripe
- „Correct“ amount of circulation is shed into wake

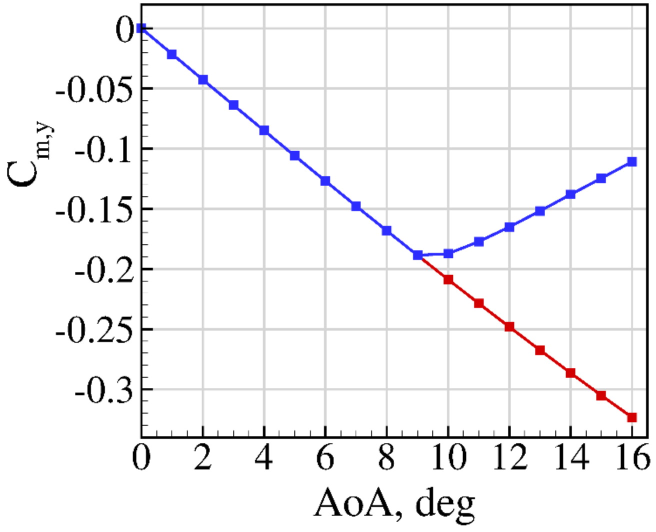


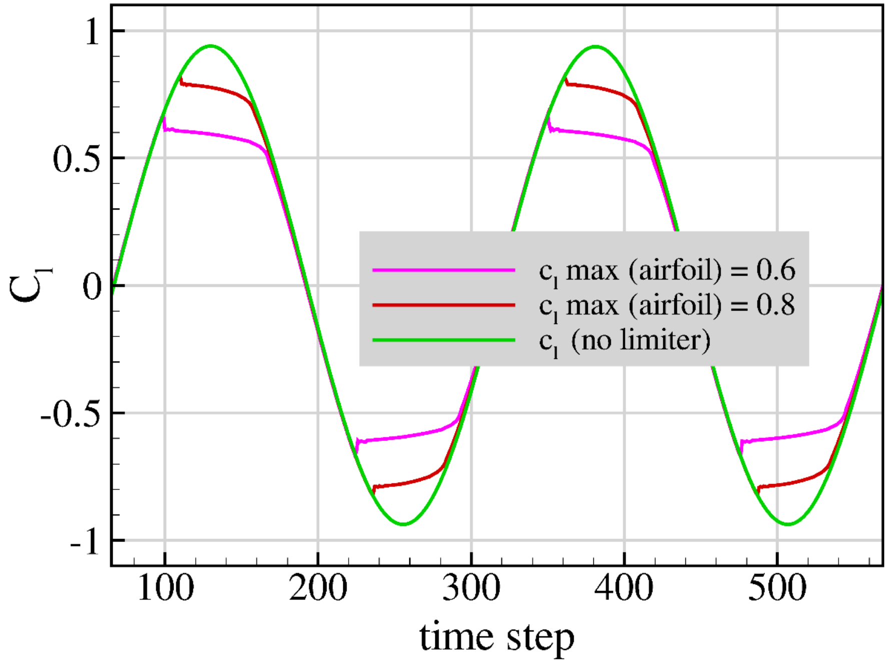


Extensions to account for aerodynamic nonlinearities (stall)

- c_l, max (airfoil section) adjusted to match maximum lift coefficient predicted from CFD simulation
- Steady polar of the wing becomes realistic when compared with CFD results
- The approach can be applied to unsteady simulations as well, but neglects dynamic effects (e.g. *dynamic stall*)



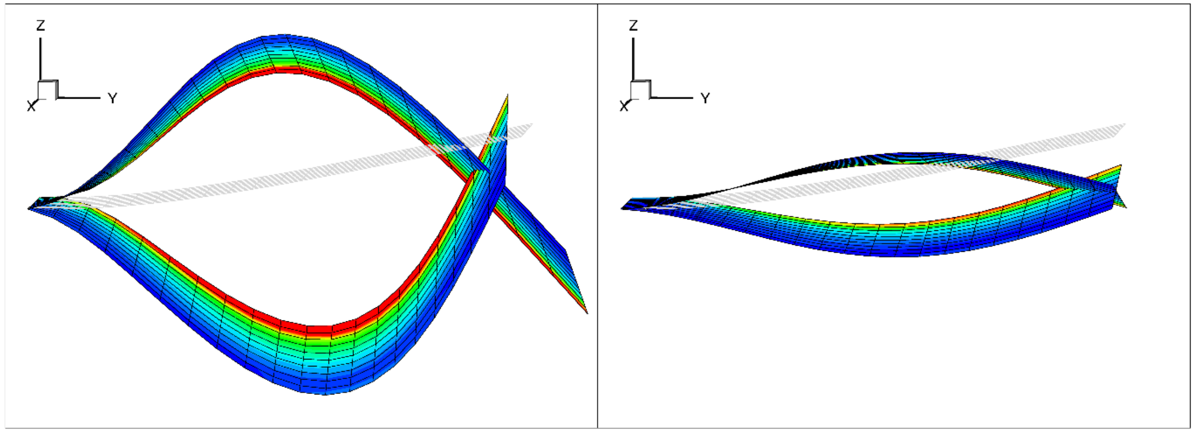




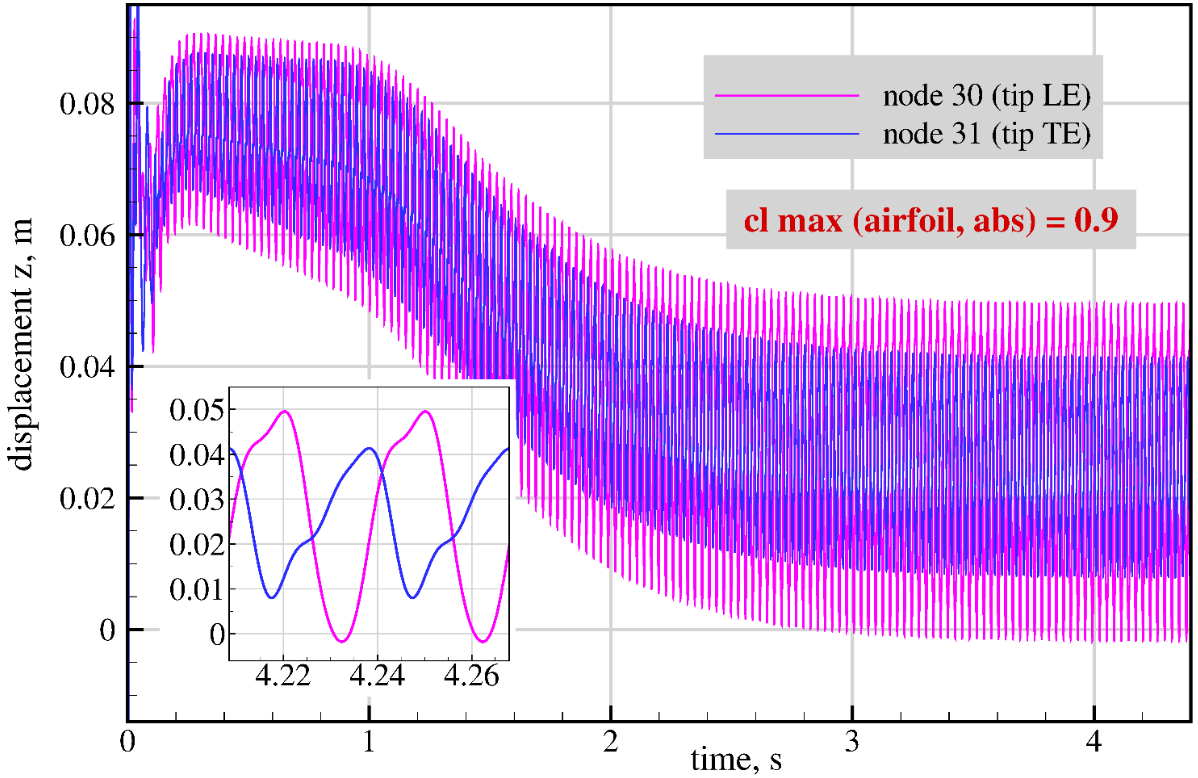
Time domain forced motion (heave) simulation

Nonlinear, Unsteady Time Domain Simulations (LCO)

- Nonlinear structural model (extended modal approach) for structural dynamics yields LCO with realistic amplitude (≈ 0.05 m at wingtip)
- Maximum airfoil lift coefficient = 0.9
- LCO frequency ≈ 33 Hz
- Significant differences in LCO shape, linear structural modes introduce nonlinear damping due to stretching of aerodynamic panels



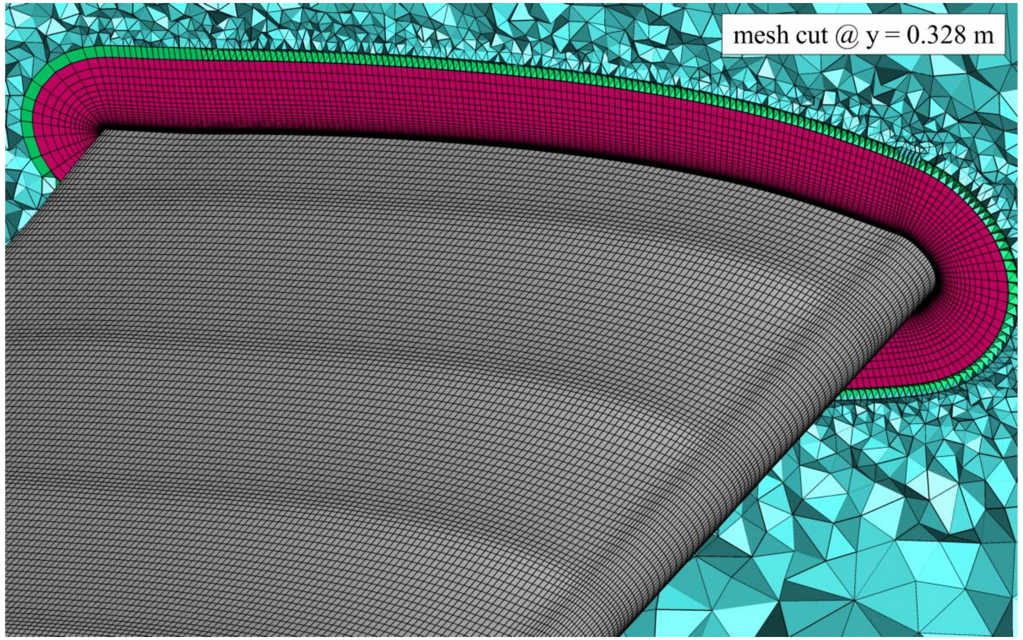
Linear modal approach   Nonlinear modal approach

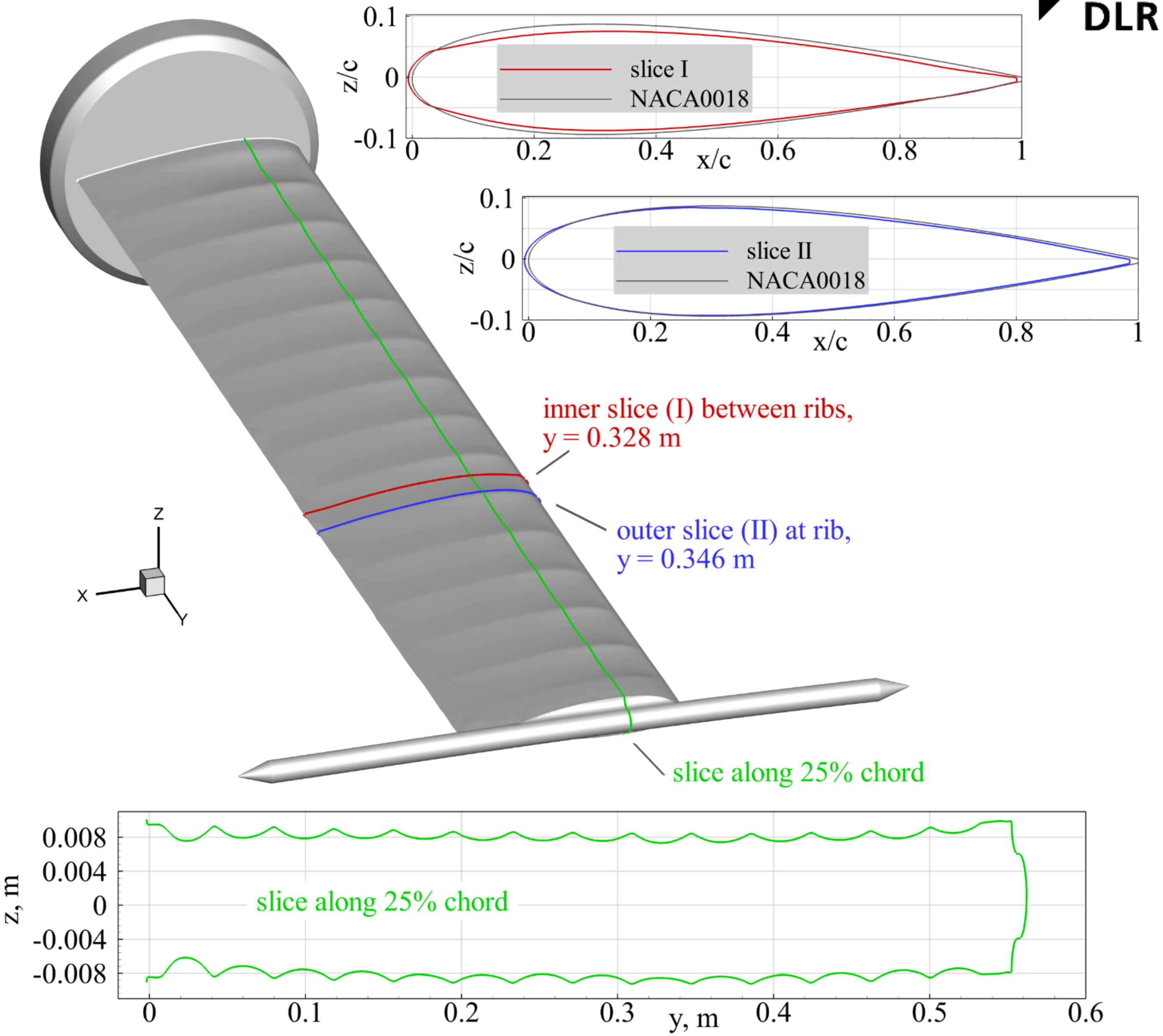


see Philipp's Master Thesis (on LDWG Teamsite)

Workflow for CFD grid generation

- The real geometry of the TU Delft Pazy Wing was 3D scanned and a high quality CAD file was generated by NASA (see Teamsite)
- A hybrid CFD grid with a structured surface mesh for the upper and lower wing was generated based on the scanned geometry

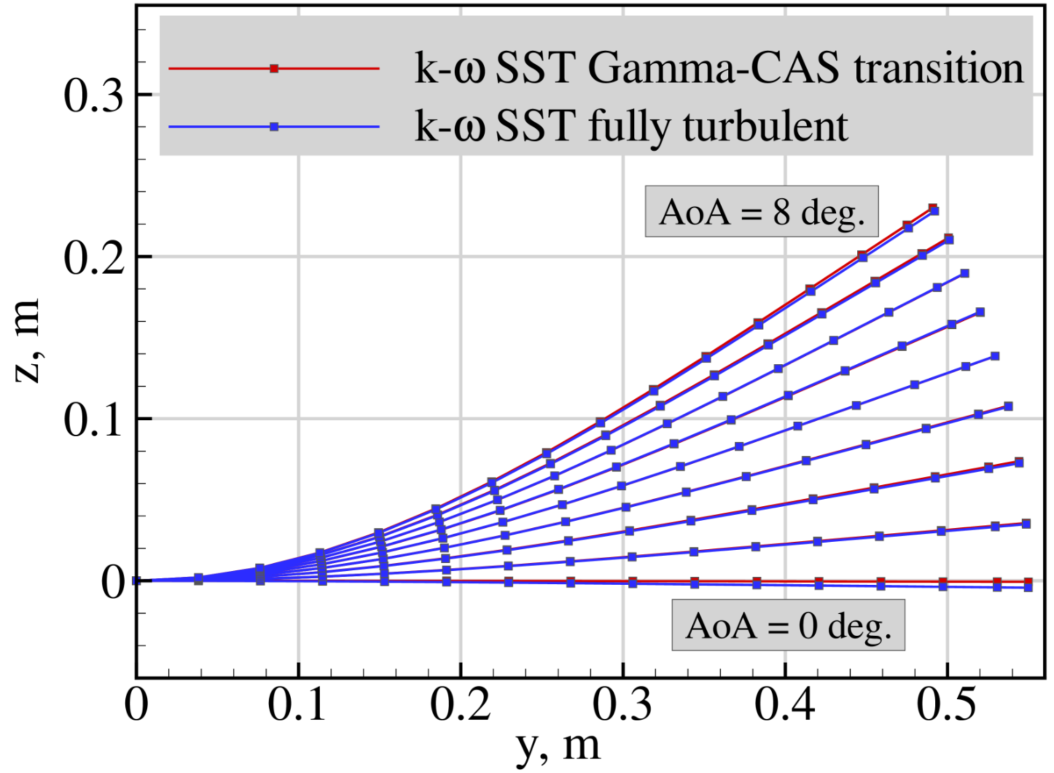


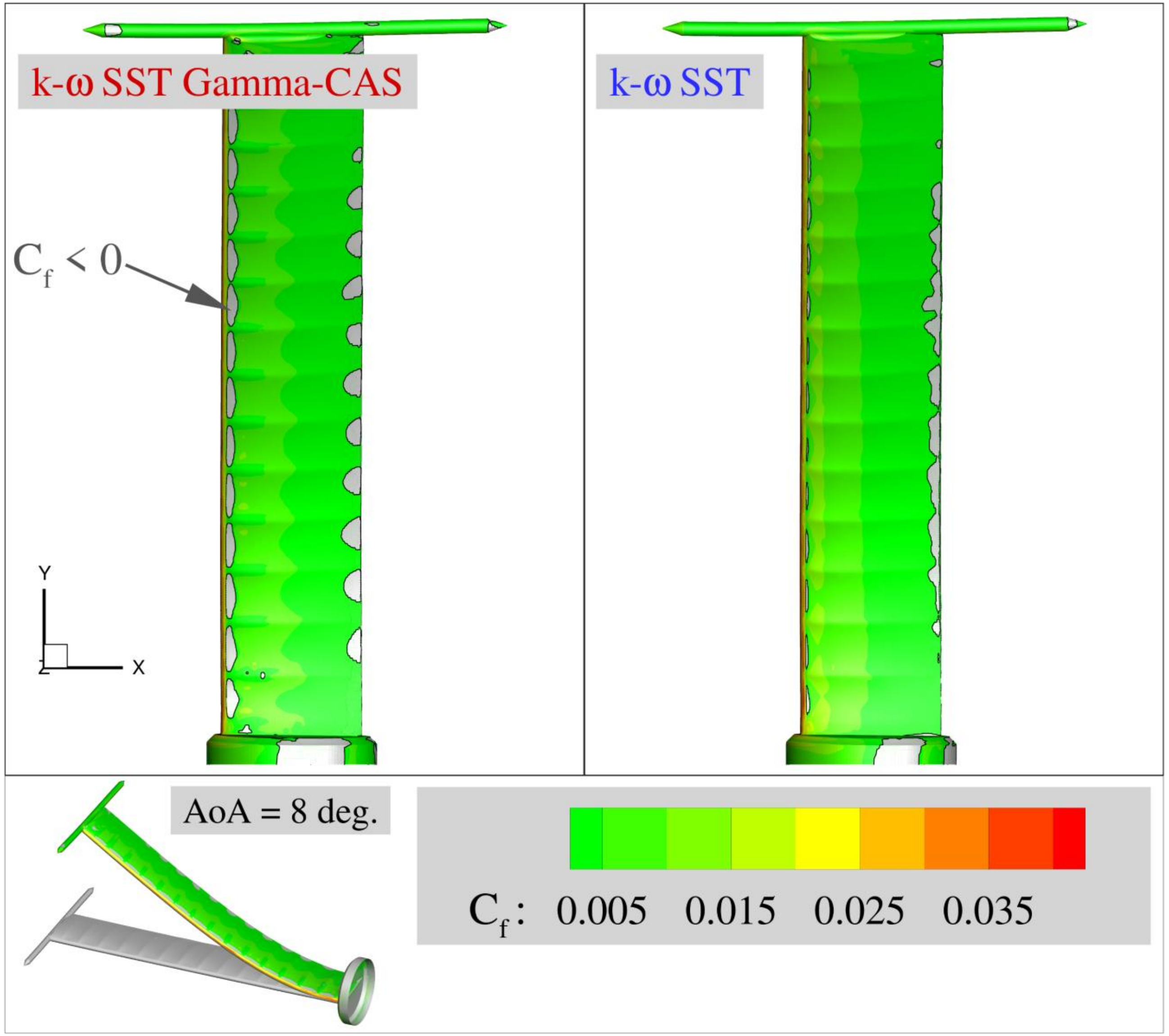


Static Coupling Results

see SciTech presentation this Tuesday

- Angle of attack polar for 50 m/s airspeed
- Slightly different structural deformations due to different Cl_{max} for fully turbulent and transitional flow





Conclusions

Summary:

- Extension of the tools used at DLR for the geometrically nonlinear analysis of aircraft structures at low speed
  - Derivation of methods for the linearization of the aeroelastic model (UVLM)
  - Combination of the linearized aerodynamic model with a linearized structural model to build a monolithic, linearized aeroelastic model of the system
  - Implement methods for stability analysis of the system
- DLR’s contribution to the Large Deflection Working Group of the AePW3
  - Static coupling simulations
  - Linear stability analysis for various angles of attack

Outlook and Next Steps:

- CFD time domain forced motion simulations with large mean angle of attack and large amplitude
- CFD time domain flutter and LCO simulations and validation with experimental results