1st Aeroelastic Prediction Workshop

Static and Forced Motion Simulations of the HIRENASD Test Case- Approaches and Results

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Approach for the static coupling simulations

- For steady calculations, the flexibility of the wing was taken into account by apploying a weakly coupled FSI simulation based on a modal approach

$$\boldsymbol{\Omega}\,\vec{q} = \boldsymbol{\Phi}^T \vec{f}_s$$

$$\vec{f}_s = \boldsymbol{H}^T \vec{f}_a$$

$\boldsymbol{\Omega}$ = Eigenvalues matrix

$\boldsymbol{\Phi}$ = Mode shape matrix

$\mathbf{H}$ = Interpolation matrix

CFD

$$\frac{d\boldsymbol{u}}{dt} + \frac{d\boldsymbol{F}(\boldsymbol{u})}{d\boldsymbol{x}} = 0$$

$$\vec{f}_s = \boldsymbol{H}^T \vec{f}_a$$

FE

$$\vec{q} = \boldsymbol{\Omega}^{-1}\boldsymbol{\Phi}^T \vec{f}_s$$

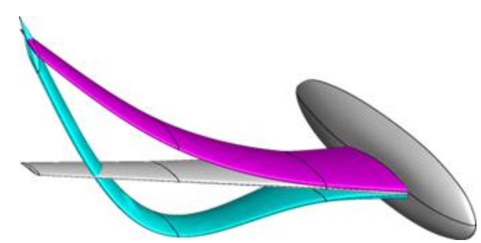
$$\vec{u}_s = \boldsymbol{\Phi}\vec{q}$$

$$\vec{u}_a = \boldsymbol{H}\vec{u}_s$$

- To reduce computational costs, the mode shapes from the FE model can be interpolated onto the aerodynamic mesh in a pre-processing step

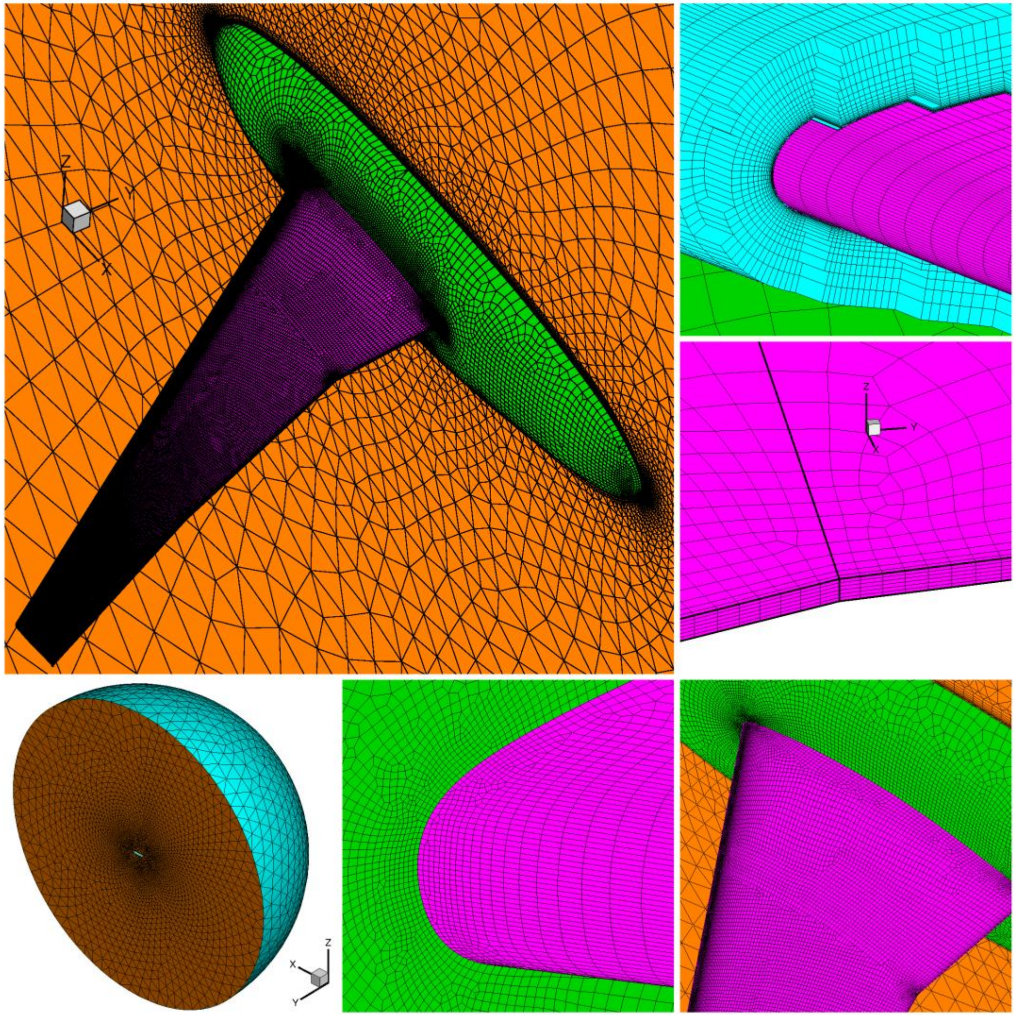
$$\vec{q} = \Omega^{-1}(\boldsymbol{H}\boldsymbol{\Phi})^T \vec{f}_a = \boldsymbol{\Omega}^{-1}\,\boldsymbol{\Phi}_a{}^T\,\vec{f}_a$$

$\boldsymbol{\Phi}_{\boldsymbol{a}}{}^{\boldsymbol{T}}$ = Aerodynamic mode shape matrix



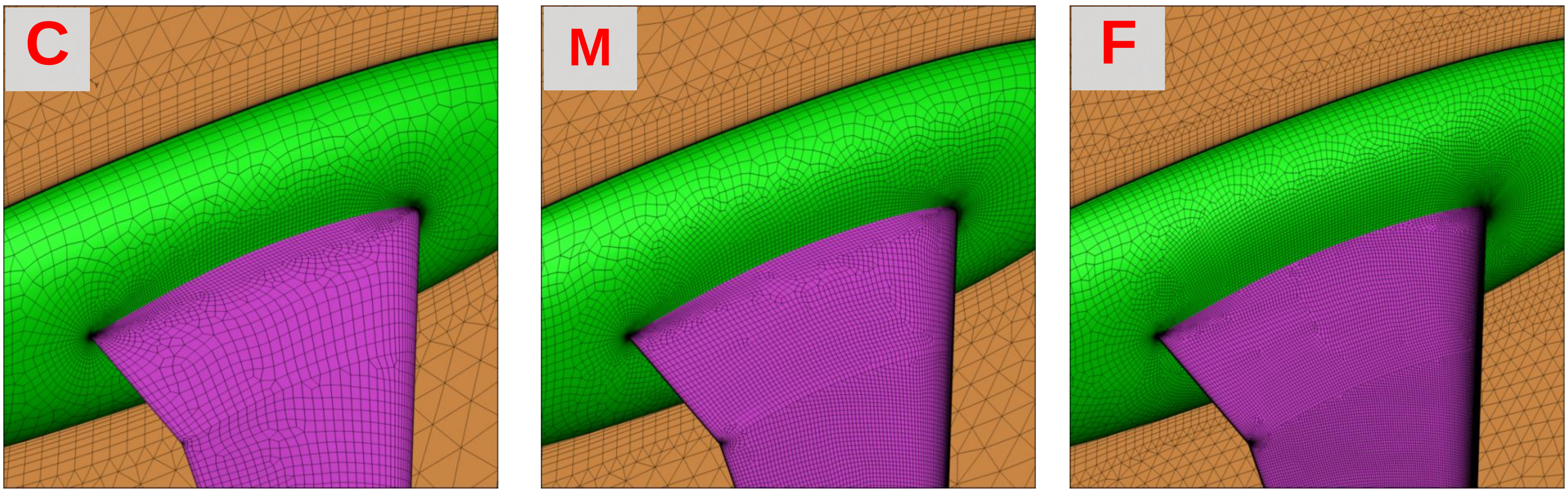
Numerical models used for the simulations

- Any aerodynamic simulations were done by the DLR TAU code, a node-based, finite-volume flow solver in ALE formulation working with hybrid grids
- Unstructured, *quad dominant* CFD meshes generated by Solar were used
- No wind tunnel walls were modeled, but a hemispherical farfield was applied



Numerical models used for the simulations

- Three different grids:



Nodes : 1 million | 2.4 million | 7.2 million

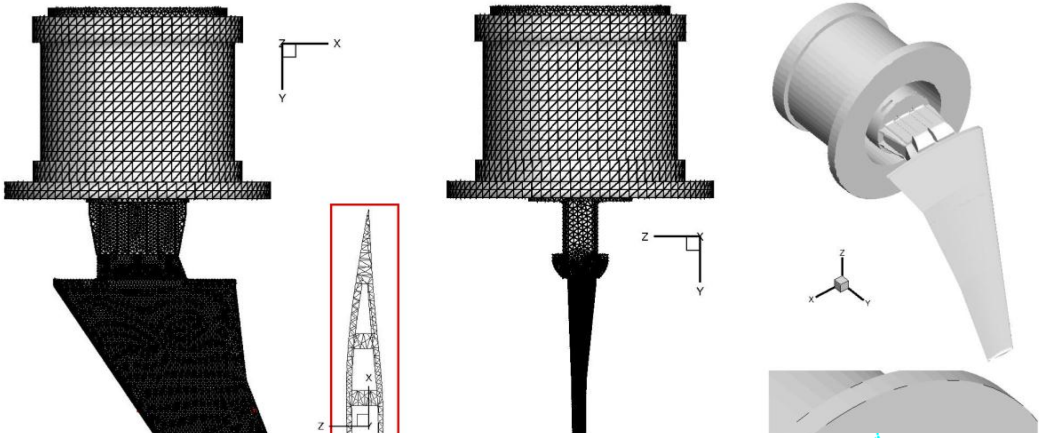
-Numerical models used for the simulations

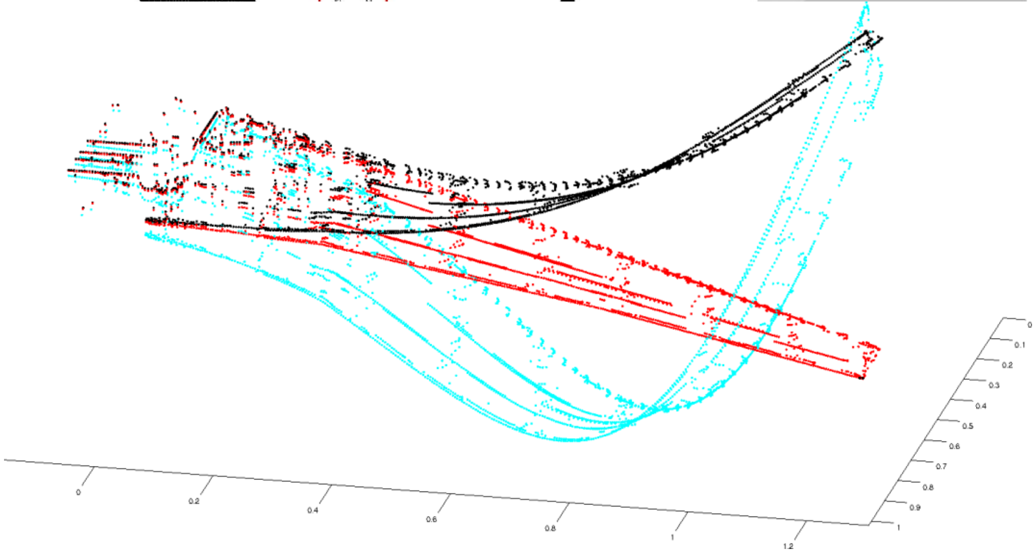
- The FE model designed by NASA that includes the balance housing was used

- NASTRAN SOL 103 is used to obtain modeshapes and eigenvalues

- Number of points was reduced using a kd-tree based method

- For the static coupling simulations, a modal basis of the twenty lowest modes was used





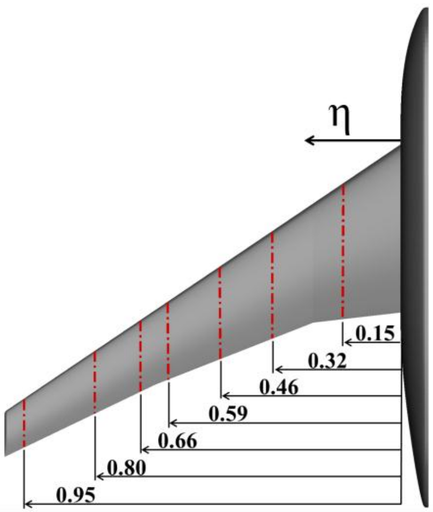
Numerical models used for the simulations

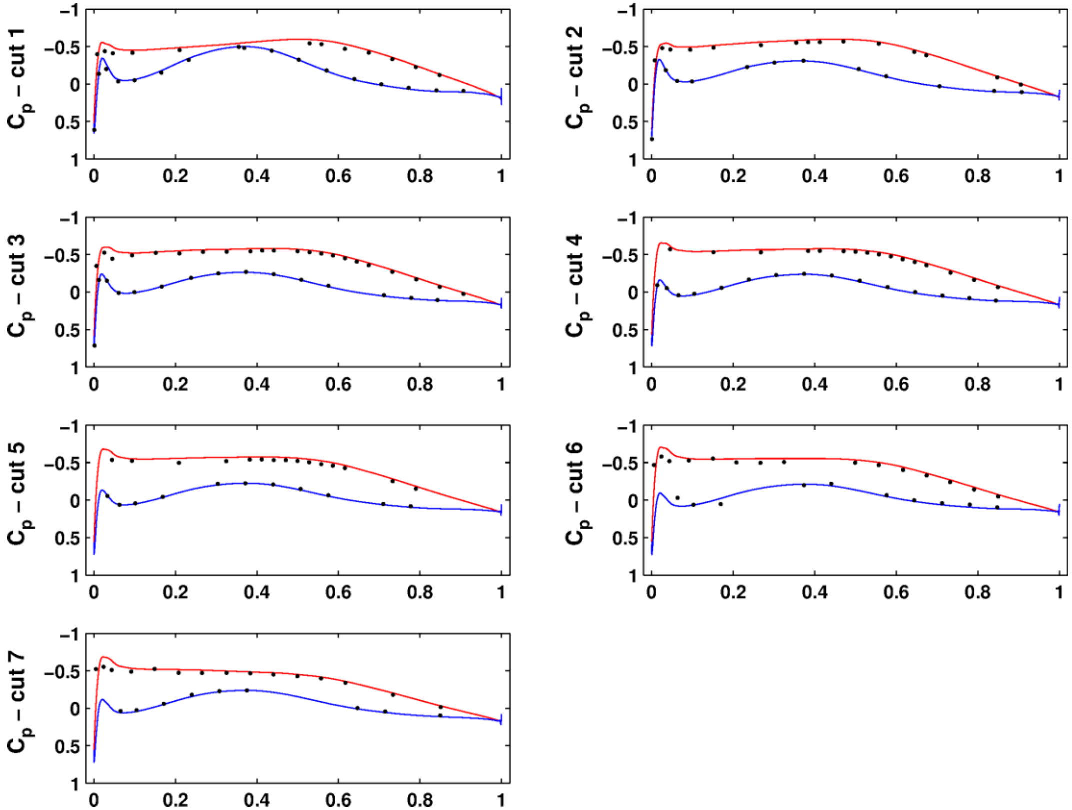
- Settings applied to the TAU code:
  - Inviscid flux calculation by Central differences (JST Scheme) with scalar dissipation
  - Convergence acceleration by multigrid
  - Local/dual time stepping for steady/unsteady simulations
  - Any calculations (RANS/URANS) used the Edward‘s modified version of the Spalart-Allmaras turbulence model
  - Moving boundary conditions employed by Radial-Basis-Function based mesh deformation

Results and validation of the steady simulations

- Comparison of the static coupling results in terms of c_P for test case **155**

- AoA = 1.5°
- Ma = 0.7, Re = 7.0 million
- Medium mesh

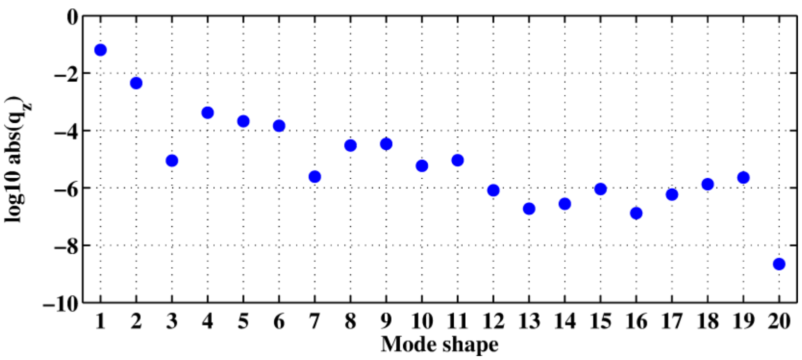


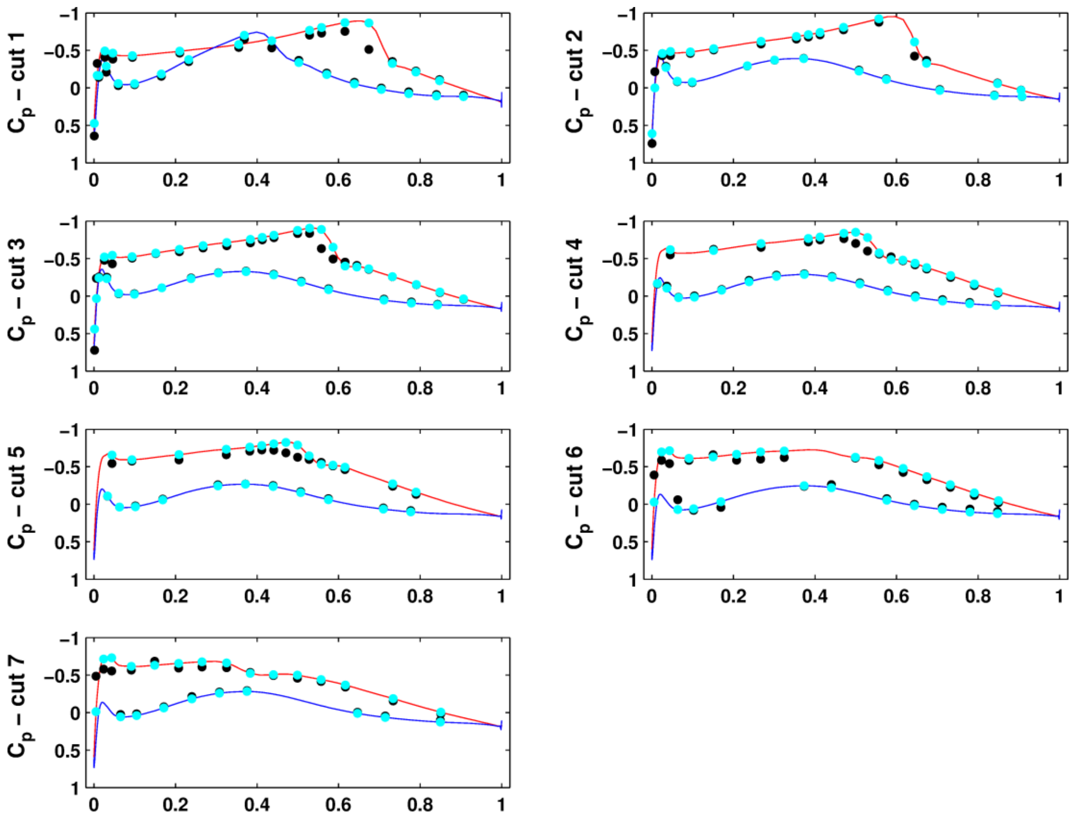


Results and validation of the steady simulations

- Comparison of the static coupling results in terms of c_P for test case **159**

- AoA = 1.5°
- Ma = 0.8, Re = 7.0 million
- Medium mesh
- Deficiency in the shock region (pressure waves)

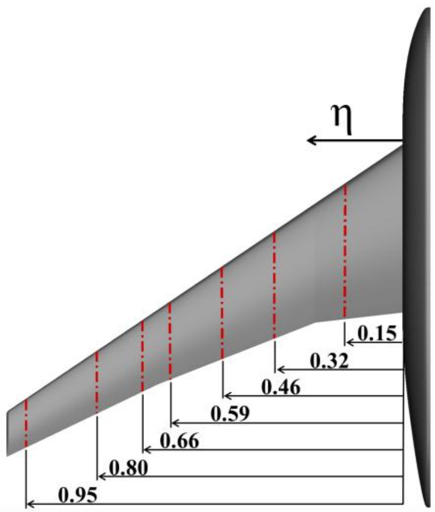


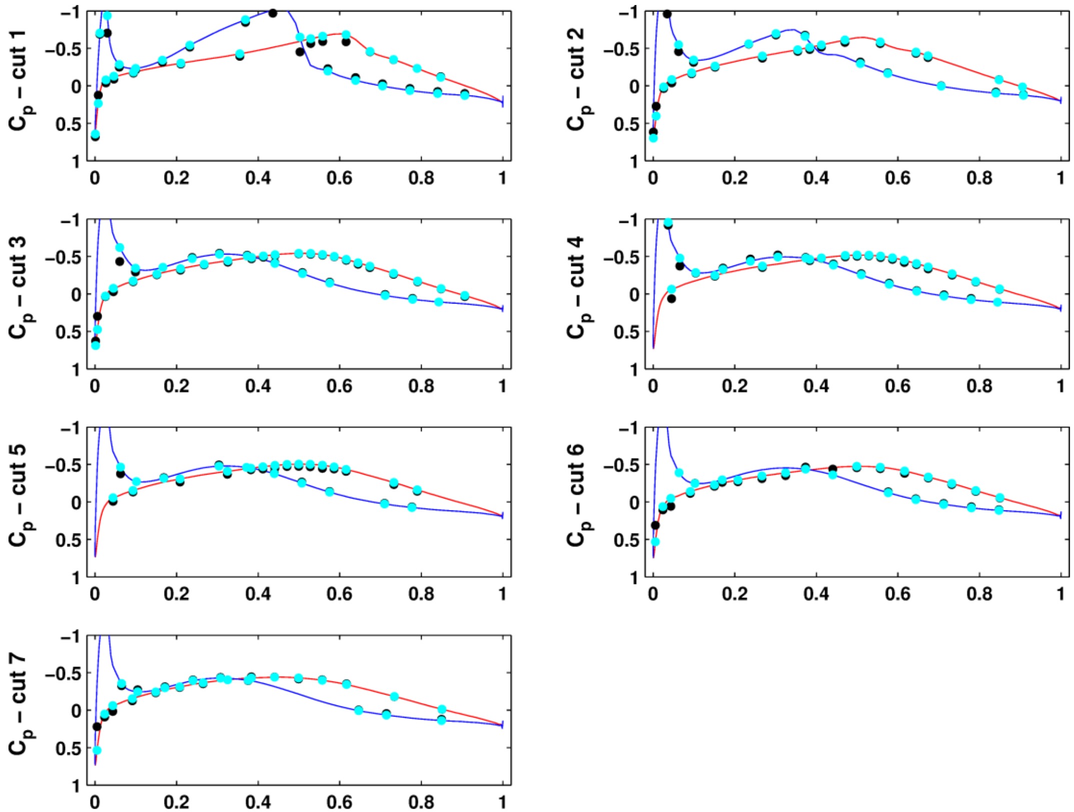


Results and validation of the steady simulations

- Comparison of the static coupling results in terms of c_P for test case **271**

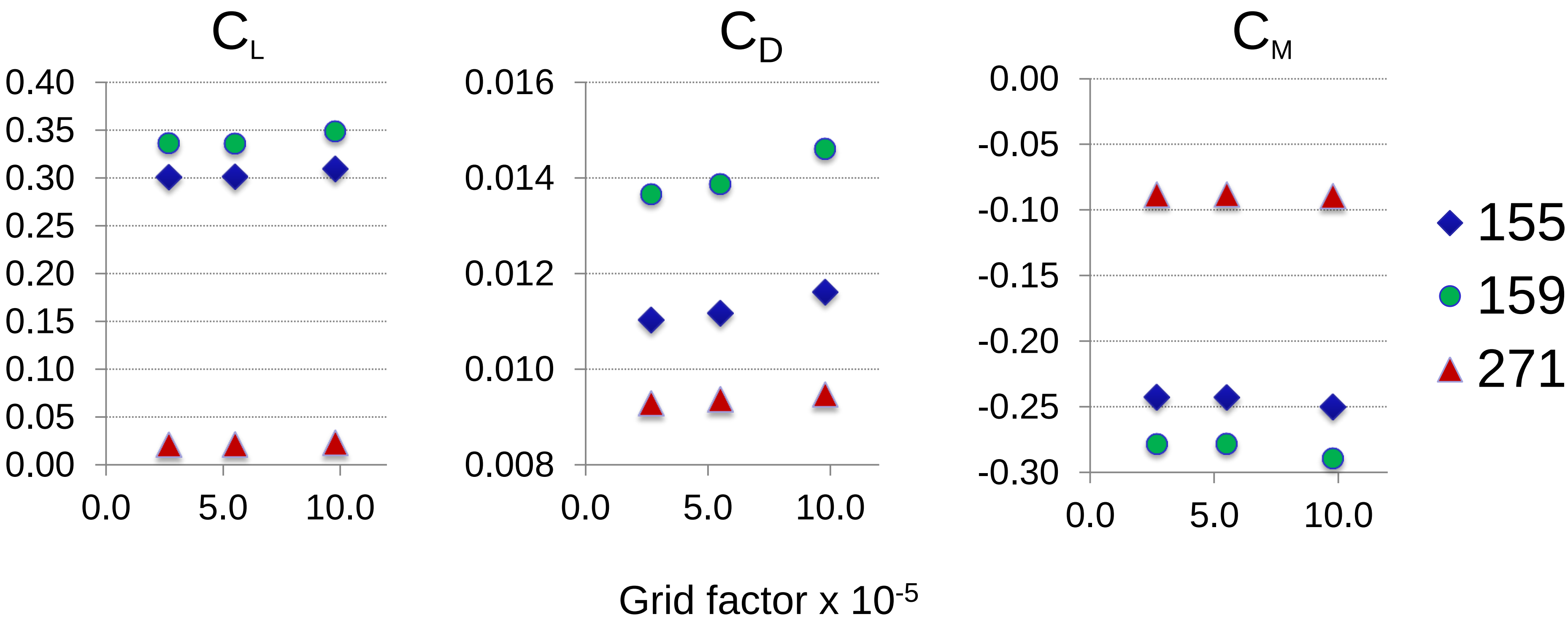
- AoA = 1.5°
- Ma = 0.8, Re = 7.0 million
- Medium mesh





Results and validation of the steady simulations

- Mesh convergence for the static coupling test cases



Approach for the unsteady forced motion simulations

- To simulate the unsteady test cases, the elastic motion of the wing in the second bending mode was applied as boundary condition during an unsteady CFD calculation

$$\vec{u}_{a,x}(t) = a_0 \boldsymbol{\Phi}_{a,x} \sin(\omega t)$$
$$\vec{u}_{a,y}(t) = a_0 \boldsymbol{\Phi}_{a,y} \sin(\omega t)$$
$$\vec{u}_{a,z}(t) = a_0 \boldsymbol{\Phi}_{a,z} \sin(\omega t)$$

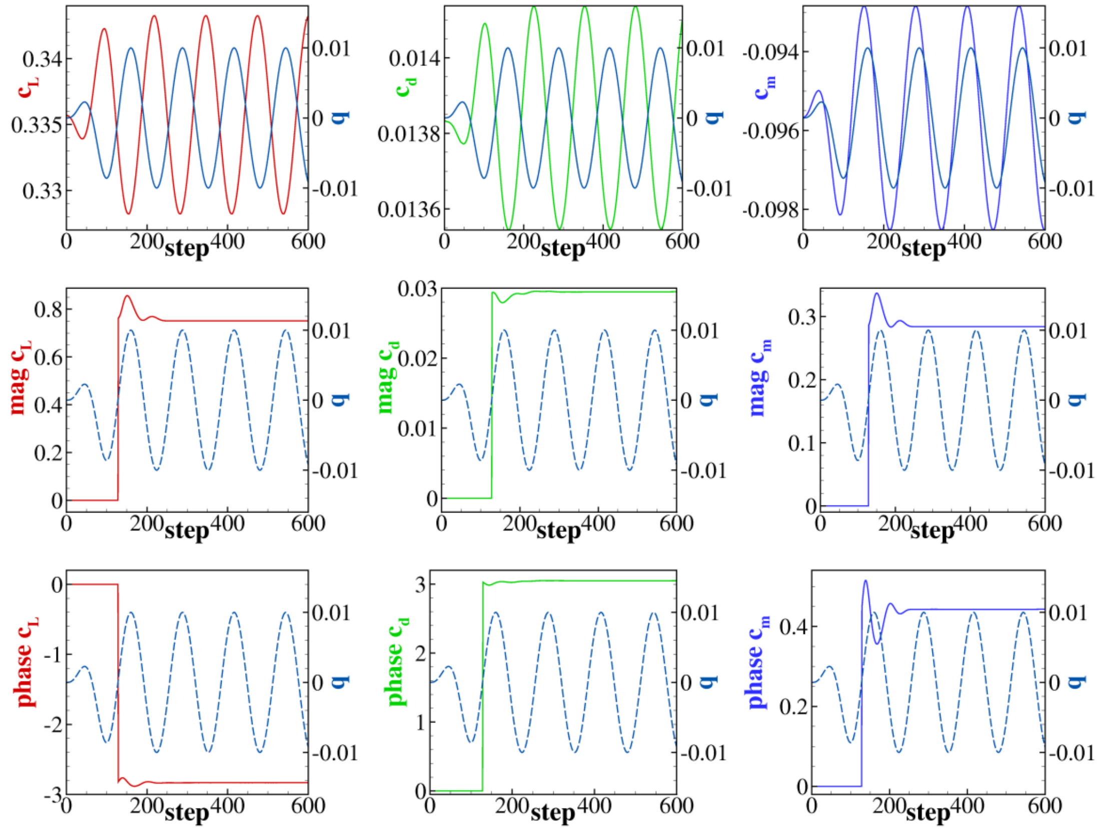
Amplitude a_0 of the simulation was chosen to match the experimental amplitude

- To obtain a transfer function of the pressure coefficient similar to the experimental data, the spectrum of c_p of the last period of oscillation is divided by the spectrum of the excitation signal (smooth function $\vec{\boldsymbol{u}}_a(t)$)

$$T_{CFD}\,(f) = \frac{FFT\,(c_p(t))}{FFT\,(a_0 \sin(\omega t))}$$

Approach for the unsteady forced motion simulations

- The following numerical parameter were used for the unsteady Forced Motion simulations:
  - Dual time stepping for time integration
  - 64/128 physical steps per period
  - Convergence in the frequency domain could be reached for integral values after approx. 2 oscillation periods



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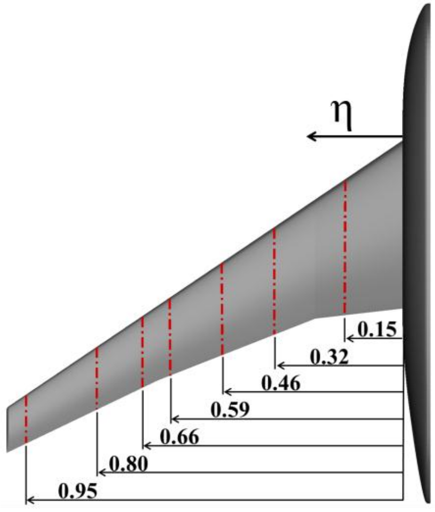
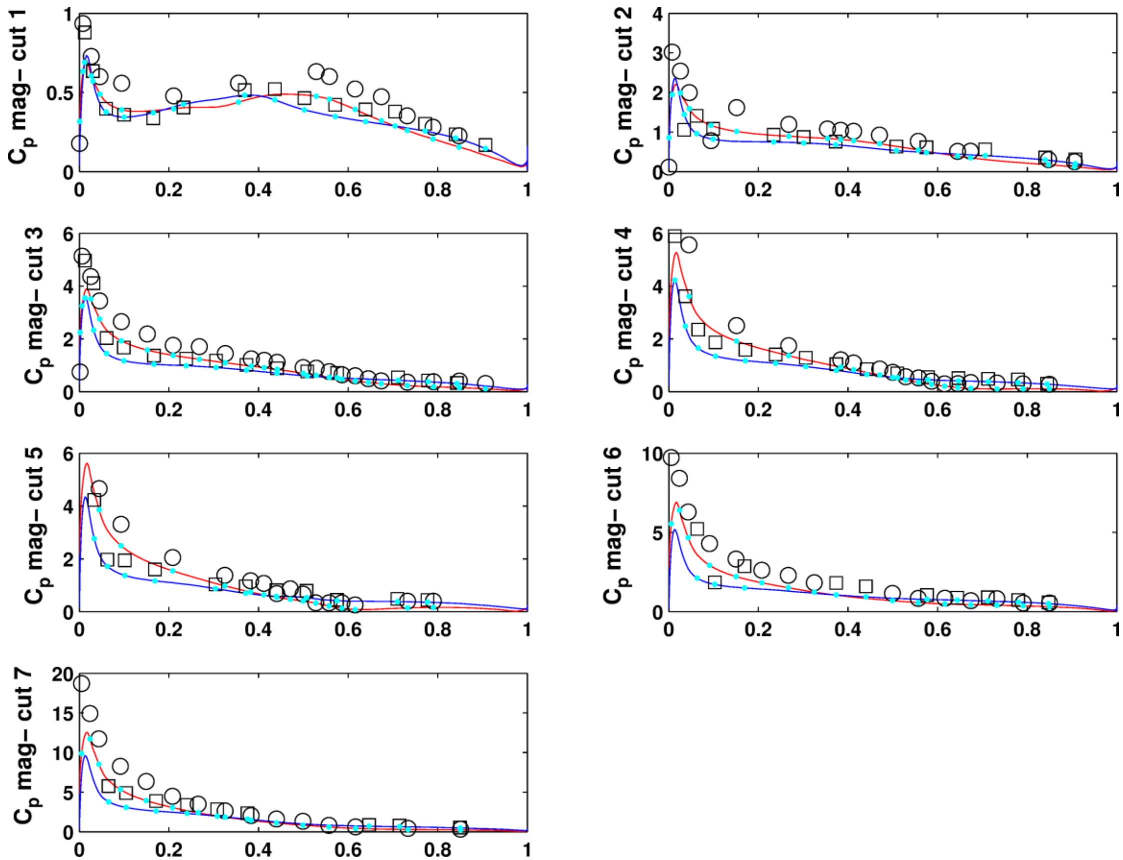
Results and validation of the unsteady simulations

- Comparison of c_p magnitude for test case 155

- AoA = 1.495°
- Ma = 0.7, Re = 7.0 million
- Medium mesh

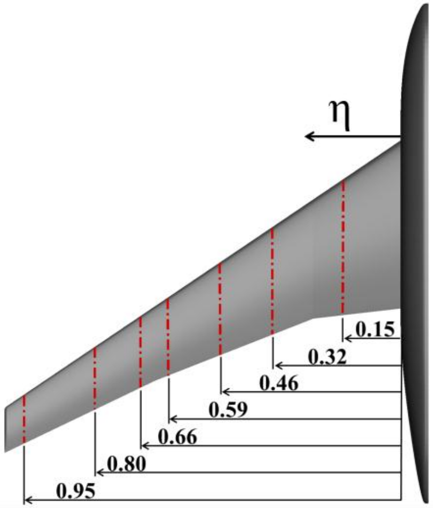


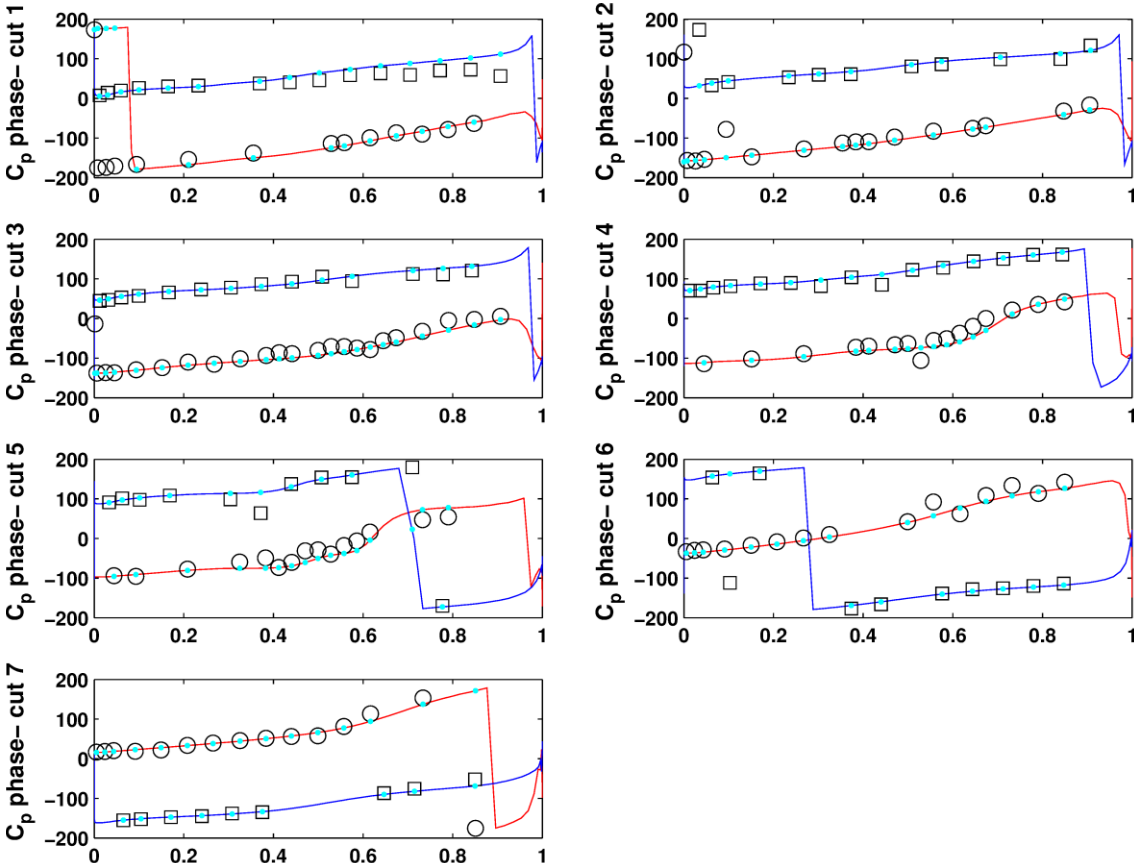


Results and validation of the unsteady simulations

- Comparison of c_p phase for test case 155

- AoA = 1.495°
- Ma = 0.7, Re = 7.0 million
- Medium mesh





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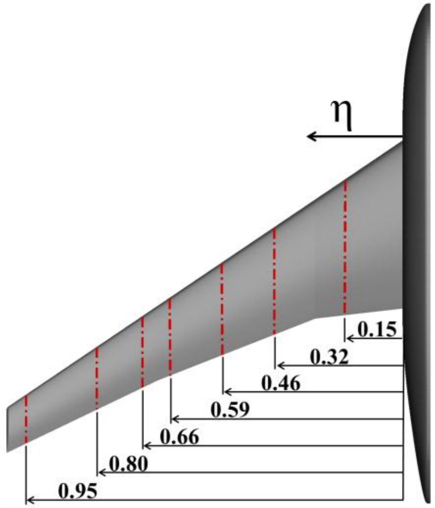
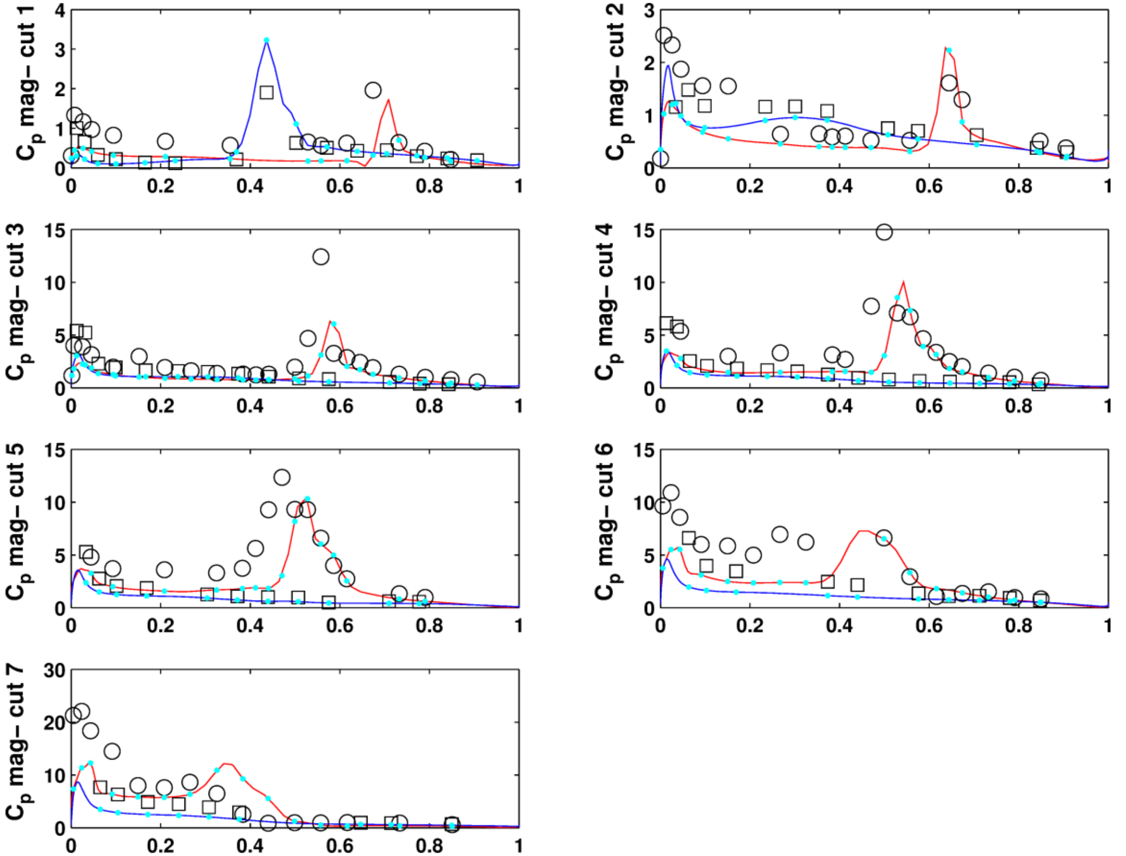
Results and validation of the unsteady simulations

- Comparison of c_p magnitude for test case 159

- AoA = 1.495°
- Ma = 0.8, Re = 7.0 million
- Medium mesh





Results and validation of the unsteady simulations

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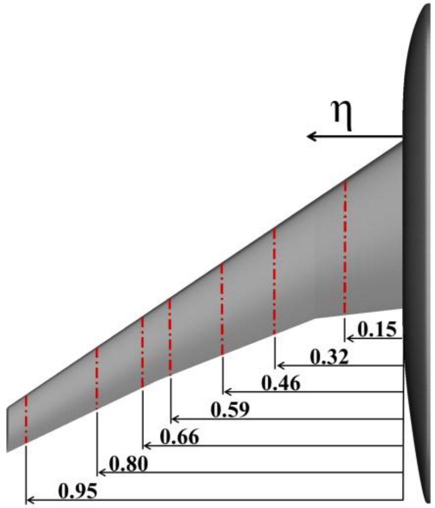

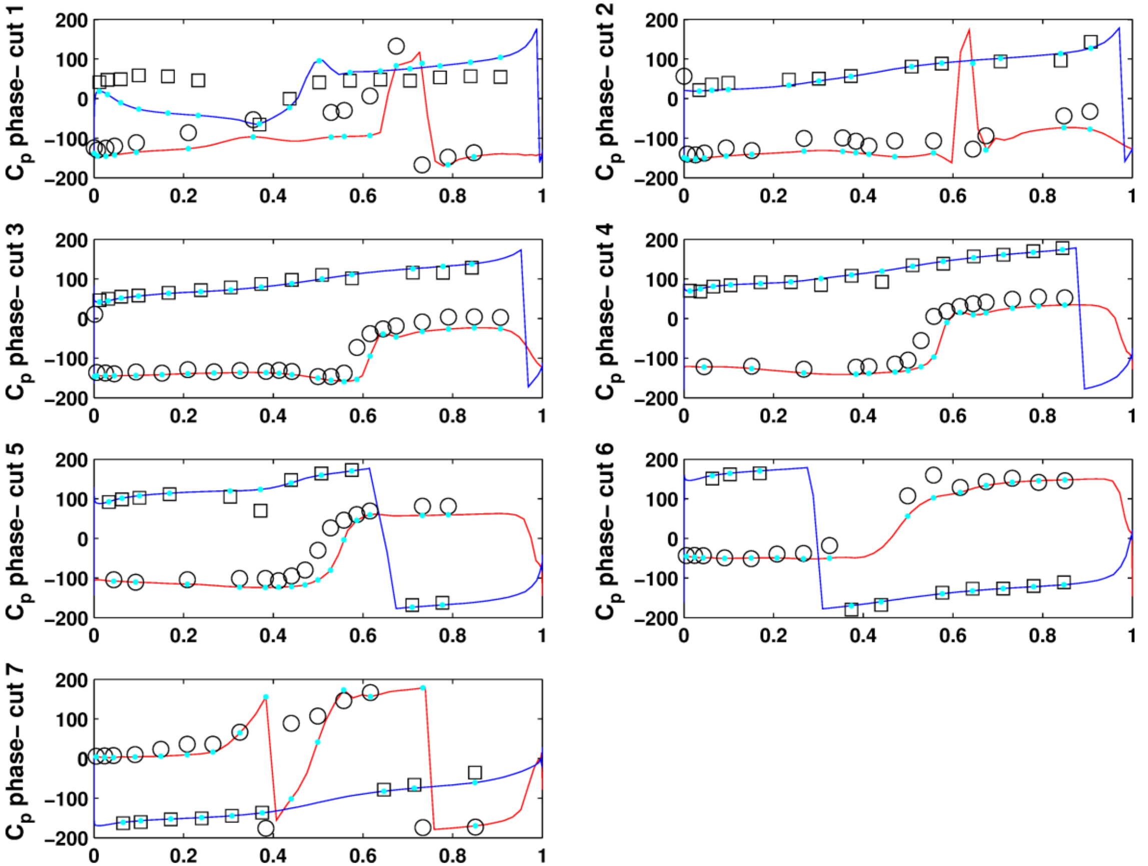

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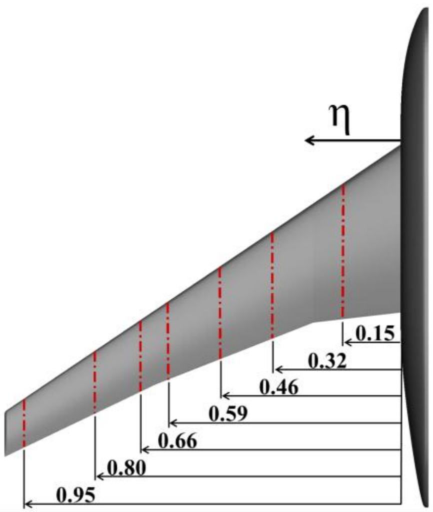
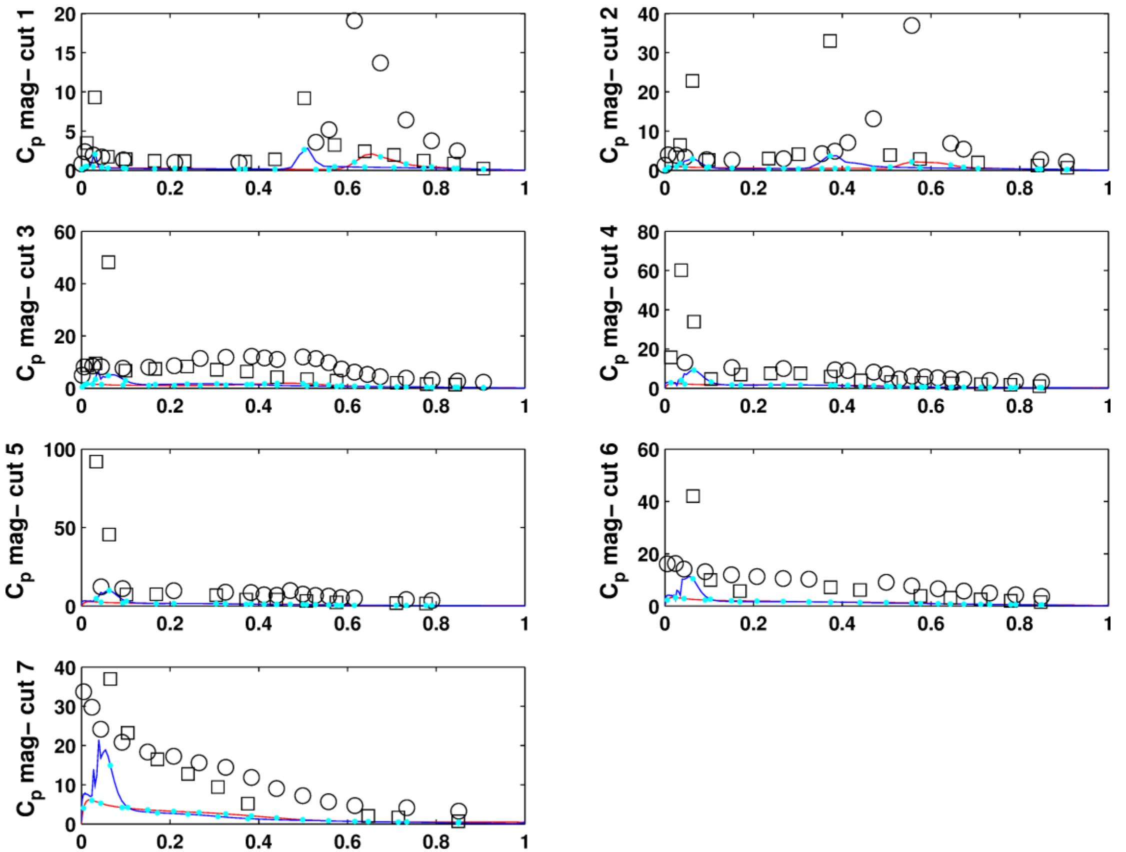
Results and validation of the unsteady simulations

- Comparison of c_p magnitude for test case 271

- AoA = 1.495°
- Ma = 0.8, Re = 23.5 million
- Medium mesh

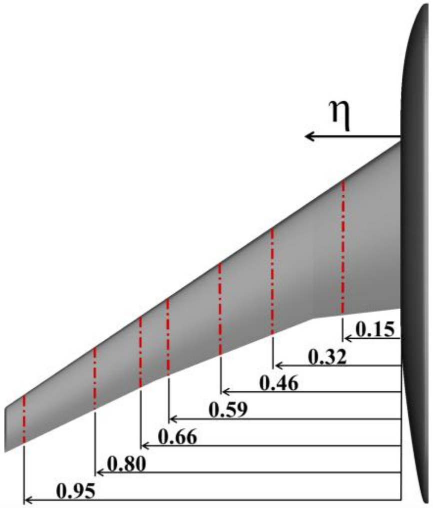


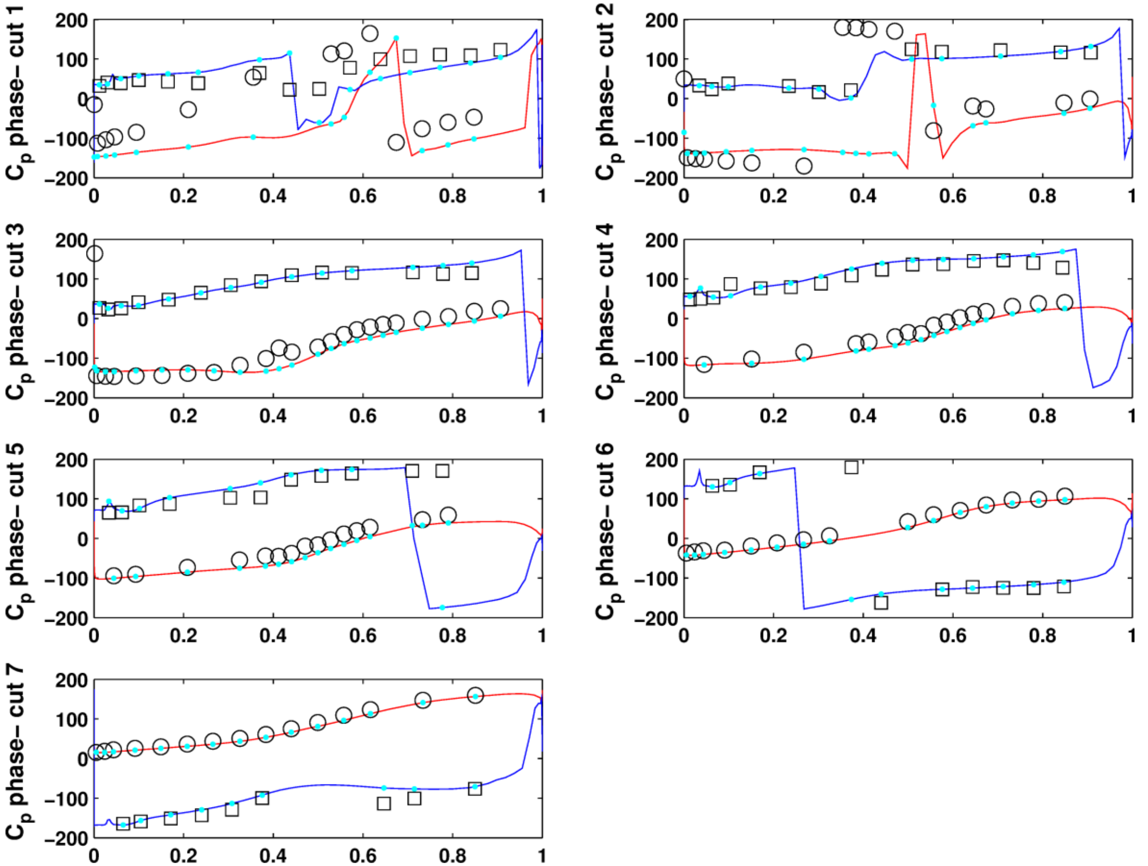


Results and validation of the unsteady simulations

- Comparison of c_p phase for test case 271

- AoA = 1.495°
- Ma = 0.8, Re = 23.5 million
- Medium mesh





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Conclusion

- Results of the *static coupling* simulations agree well with experimental data:
  - Modal approach seems sufficient for the calculation of the steady aeroelastic equilibrium
- Results of the unsteady forced motion simulations agree well with experimental data with respect to c_p phase
- Differences occur for c_p magnitude, further clarification is necessary by considering at least:
  - Shock location (Turbulence model?)
  - Amplitude of the motion
  - FE modelling
  - Experimental data

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Thank you for your attention

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