Fluid-Structure Coupling Methodology Effect

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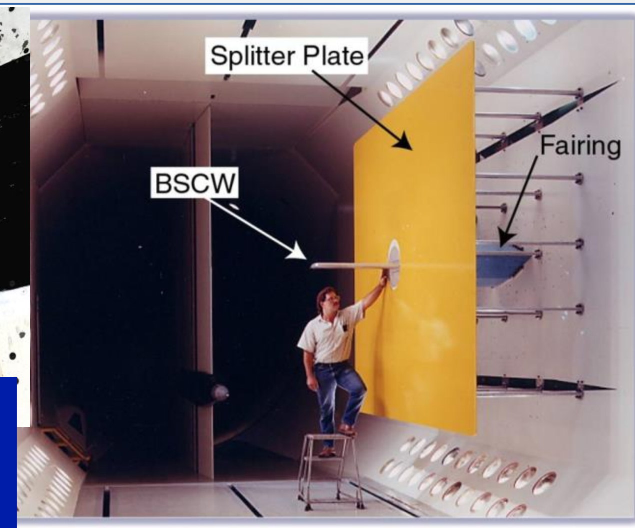
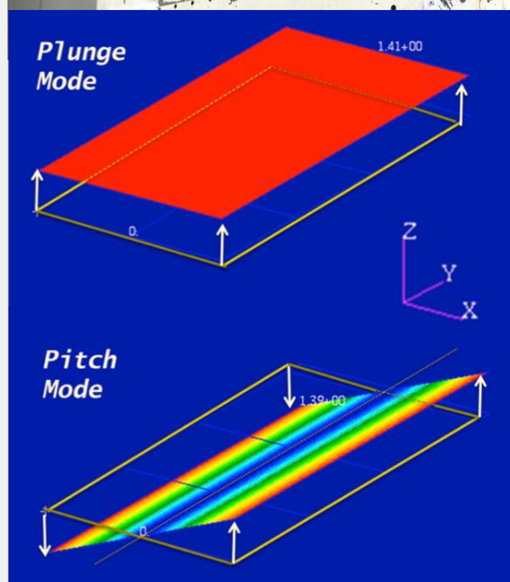
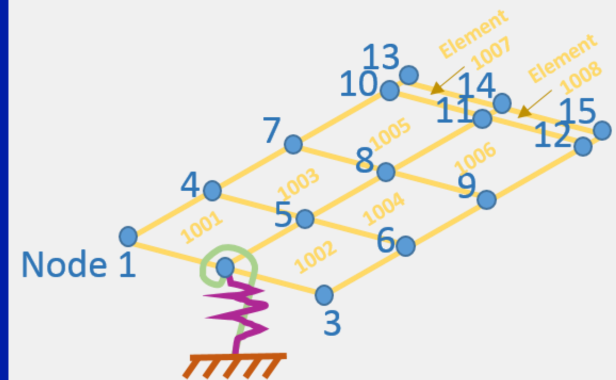
The Benchmark Super-Critical Wing

- Tested in the NASA-TDT facility
- The NASA pitch and plunging apparatus (PAPA) was used for the aeroelastic test
- A linear structural FE model was provided by NASA (AePW) with frequencies matched to WT modal data: 5.20 Hz (pitching) and 3.33 Hz (plunging)

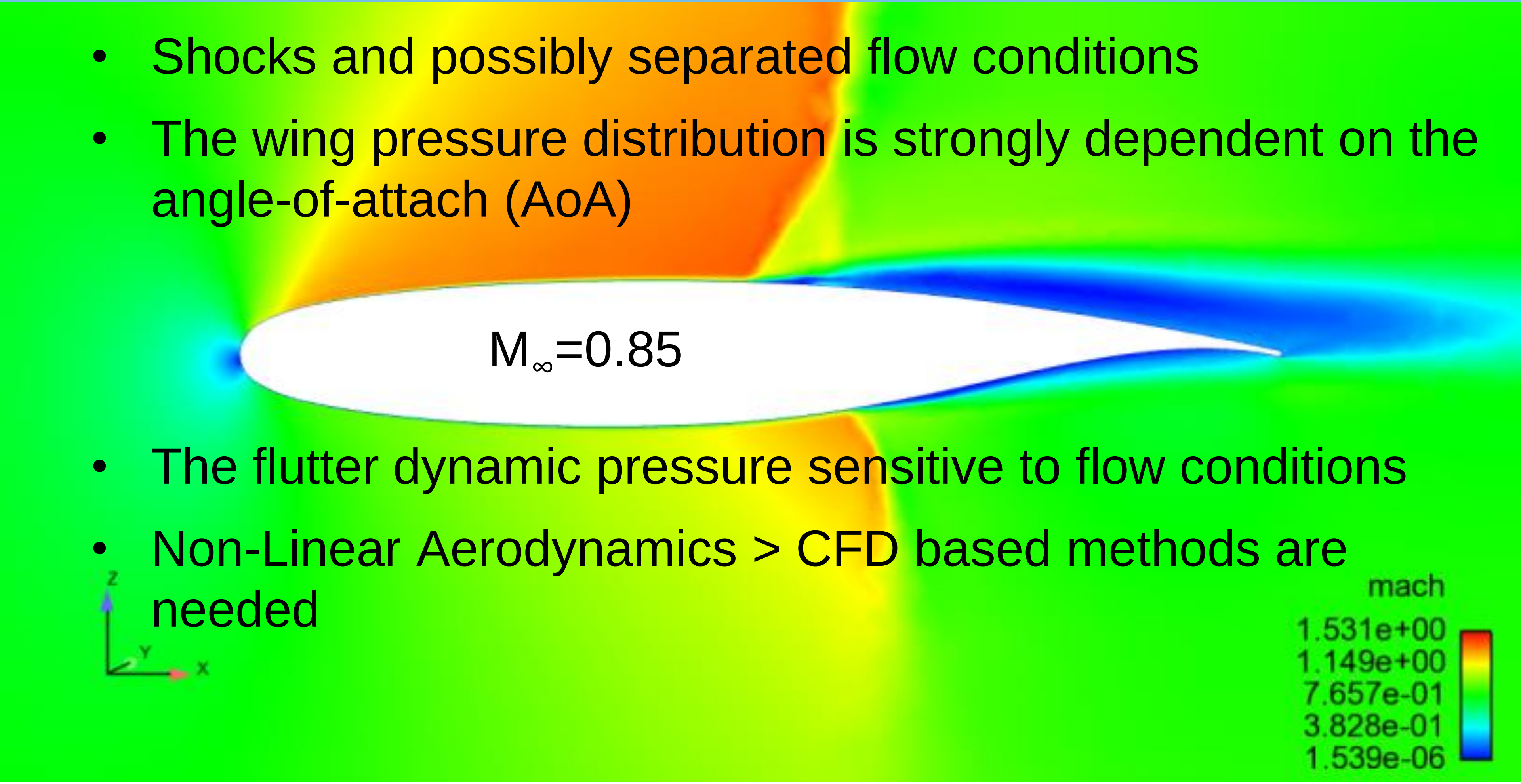






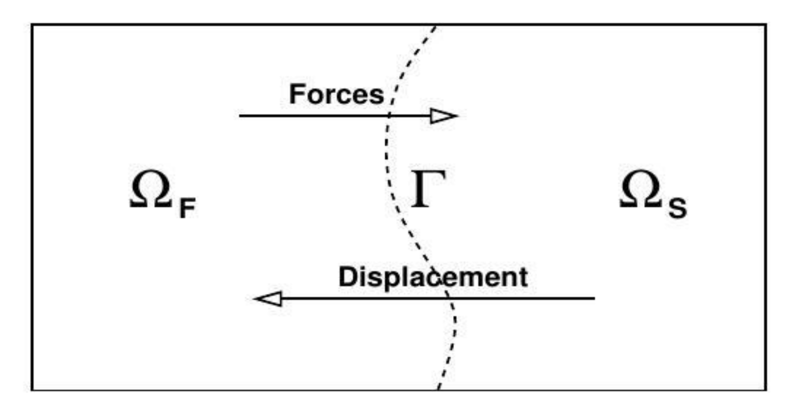
The Transonic Region $M_\infty < 1$

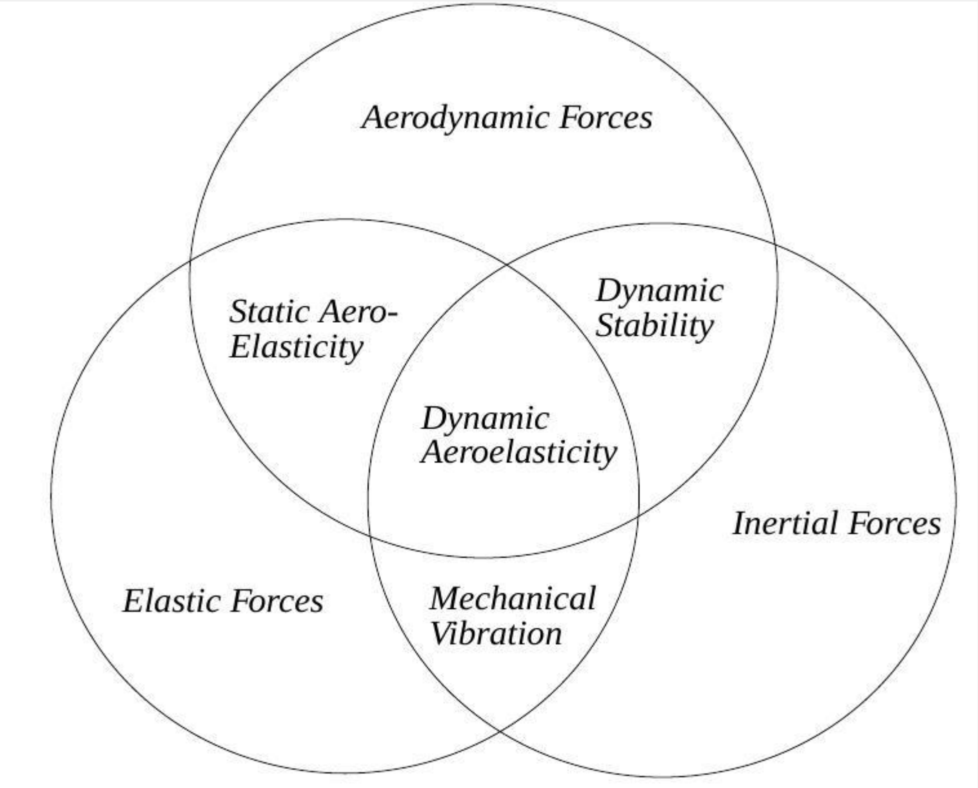
- Shocks and possibly separated flow conditions
- The wing pressure distribution is strongly dependent on the angle-of-attach (AoA)



- The flutter dynamic pressure sensitive to flow conditions
- Non-Linear Aerodynamics > CFD based methods are needed

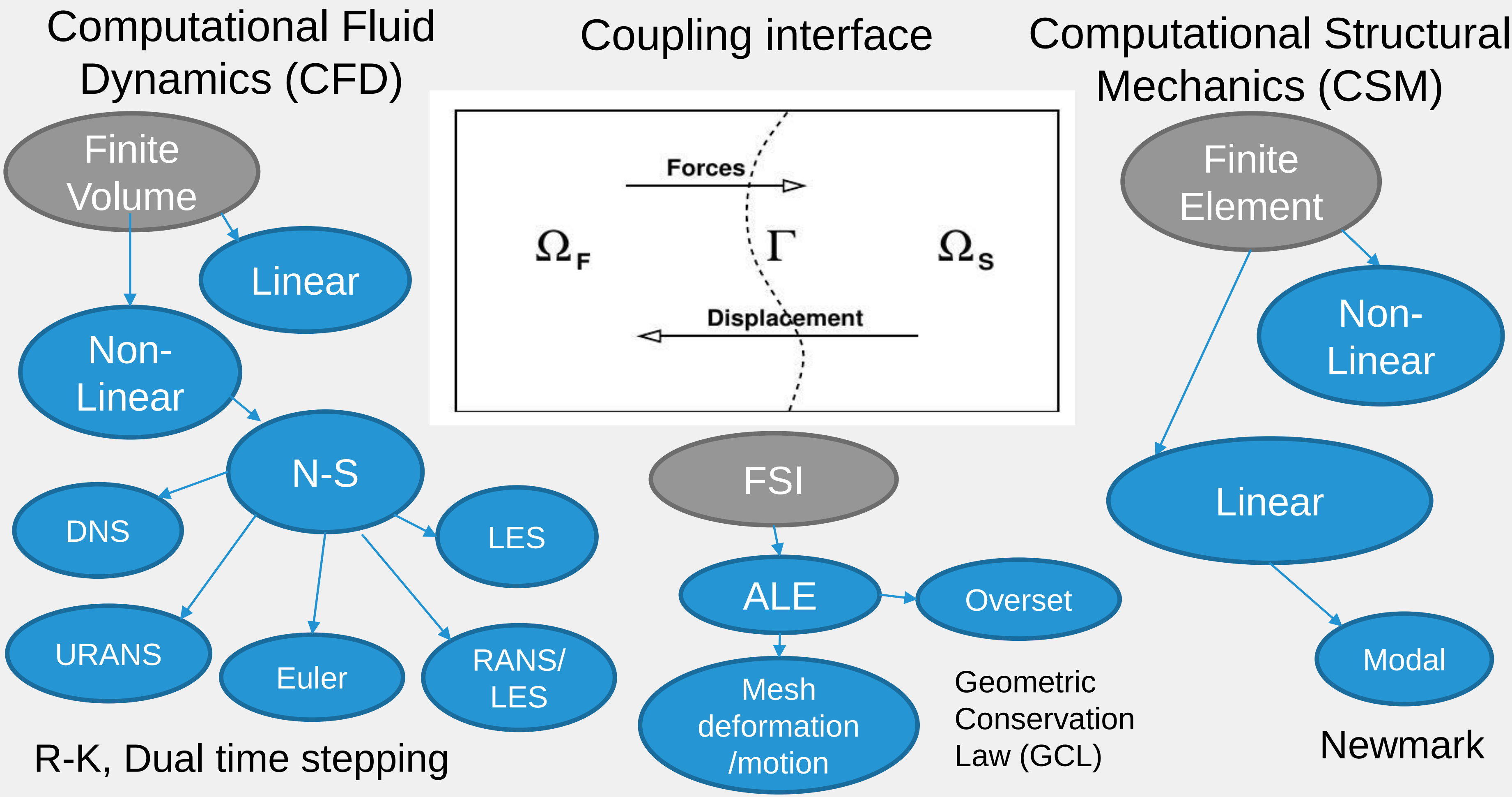
Computational Fluid-Structure Interaction



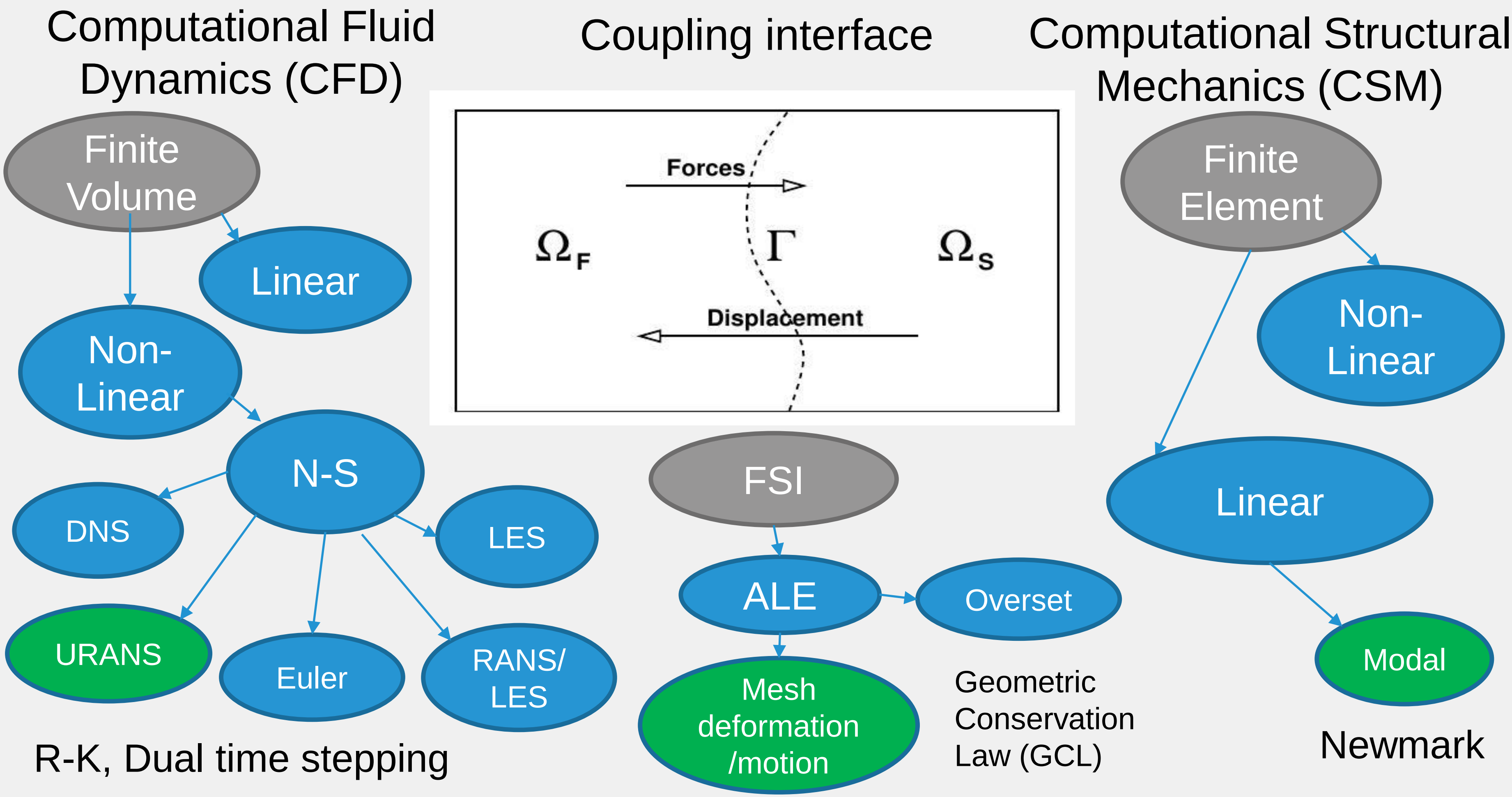


- Monolithic approach
- Staggered approach
  - Different spatial and temporal requirement
  - CFD and FEM

Computational Fluid-Structure Interaction



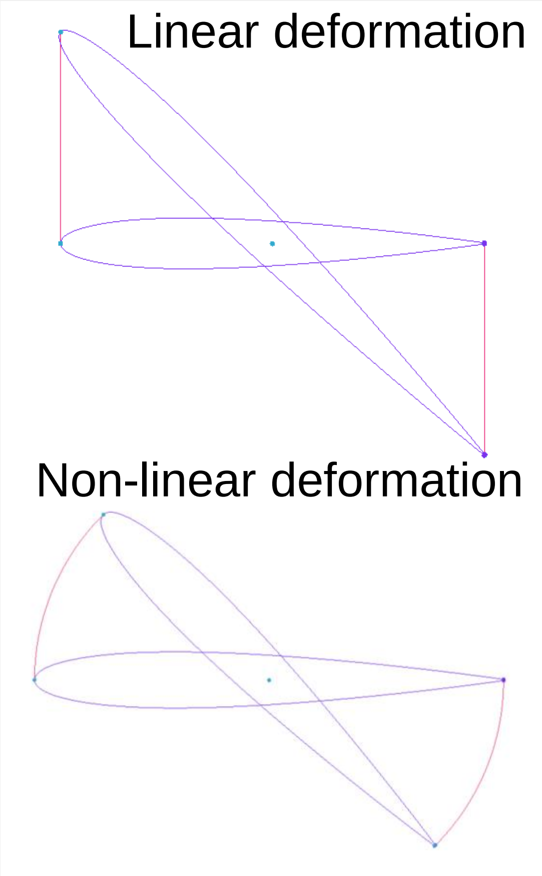
Computational Fluid-Structure Interaction



Mesh Motion vs. Mesh Deformation

Wing is considered rigid

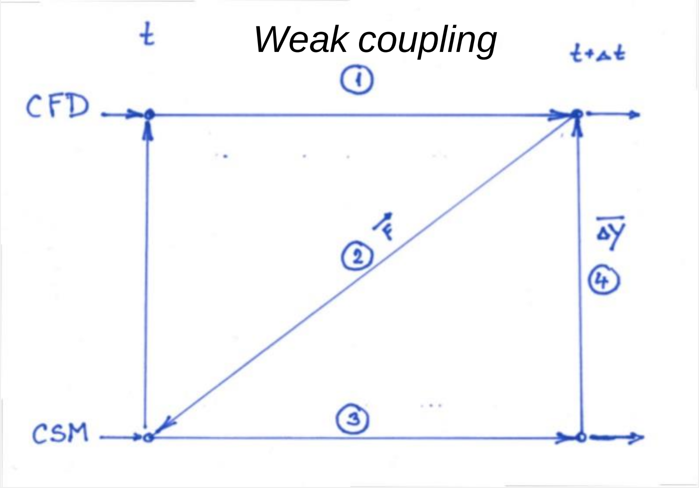
- Only two degrees-of-freedom motion (pitch and plunge)
- CFD mesh can be therefore considered as rigid and instead of deforming, it can be moved (mesh motion only)
  - The pitch and plunge motion are determined using the modal coordinates
  - Time saving by avoiding mesh deformation
- The airfoil will keep its original shape but the linearity assumption on the CFD side is not valid any more

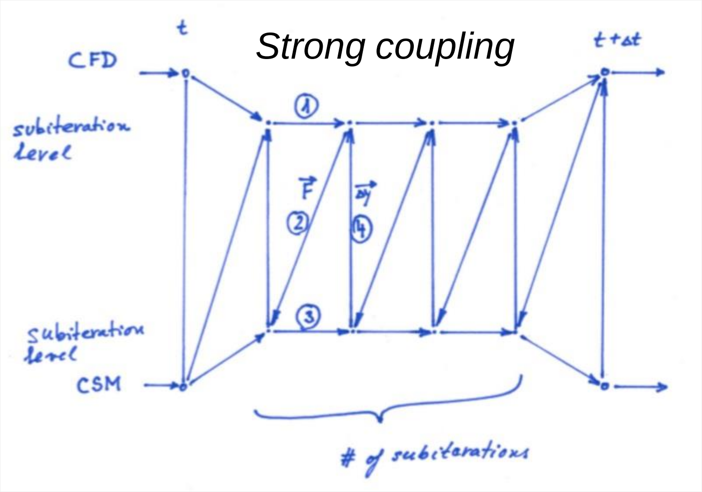


Time Synchronization

Time synchronization (coupling)

- On sub-iteration level – “strongly coupled scheme” (Farhat et. al…)
- Every time step – weak coupling
  - Do not have any special treatment of the boundary conditions due to coupling, the scheme is therefore of the first order in time





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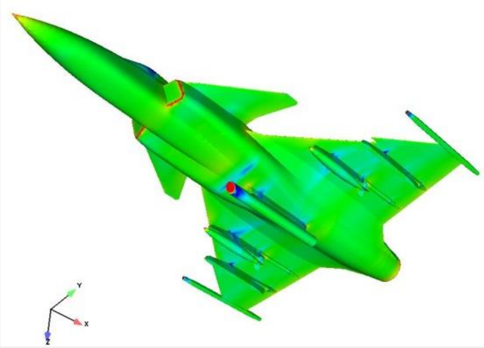
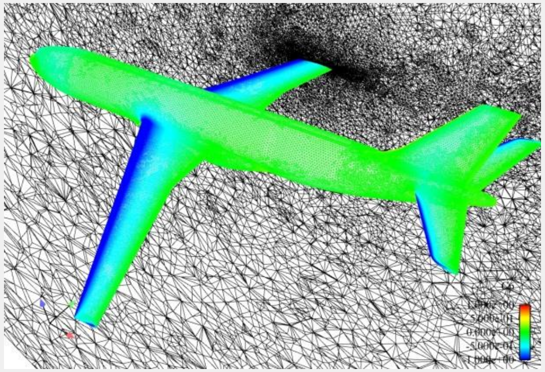
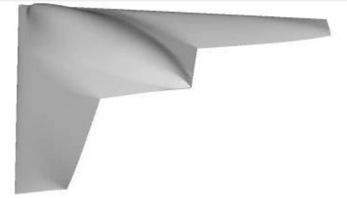
Edge – a CFD code for unstructured grids

- Independent in-house code, developed since 1997 at FOI (and former FFA)
- State-of-art flow solver for the compressible Euler and Navier-Stokes equations
- Steady-state and time dependent solutions on unstructured grids
- Fully parallel, scalable, no size limit. High efficiency
- Developed in collaboration with selected external partners. Used also in teaching and for research at different universities
- Saab Aerosystems main CFD tool

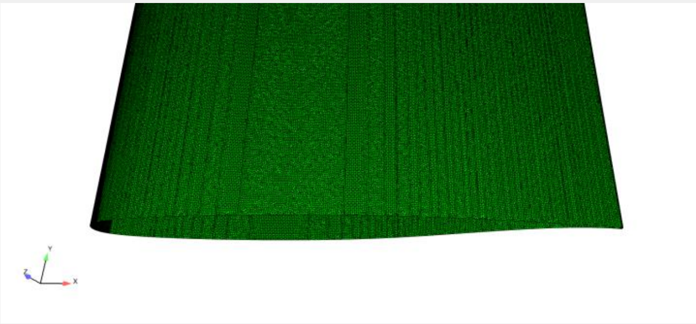


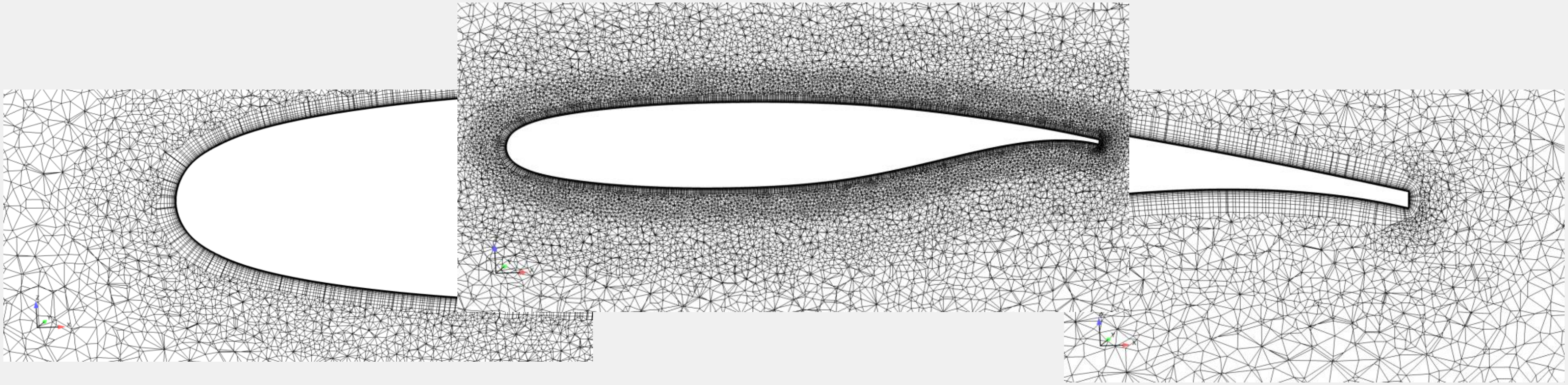




The CFD Mesh

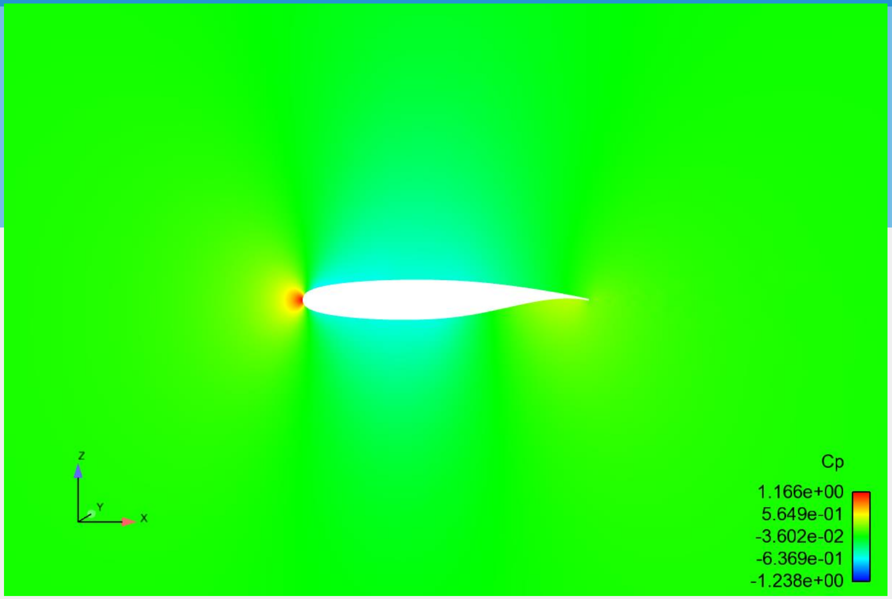
- CFD mesh made according to the meshing guide from AePW-I
  - The mesh used here is a medium, size unstructured mesh having about ~13 mil points

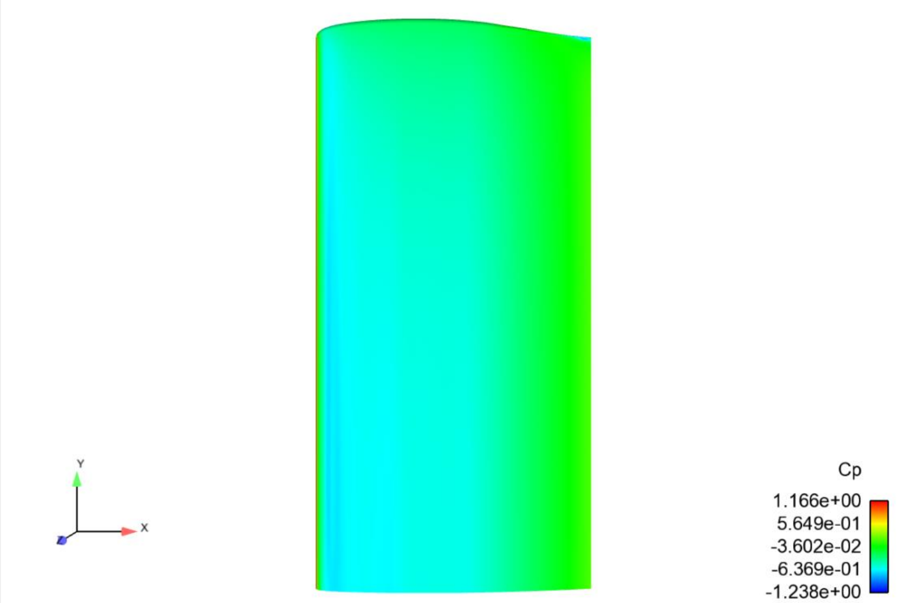


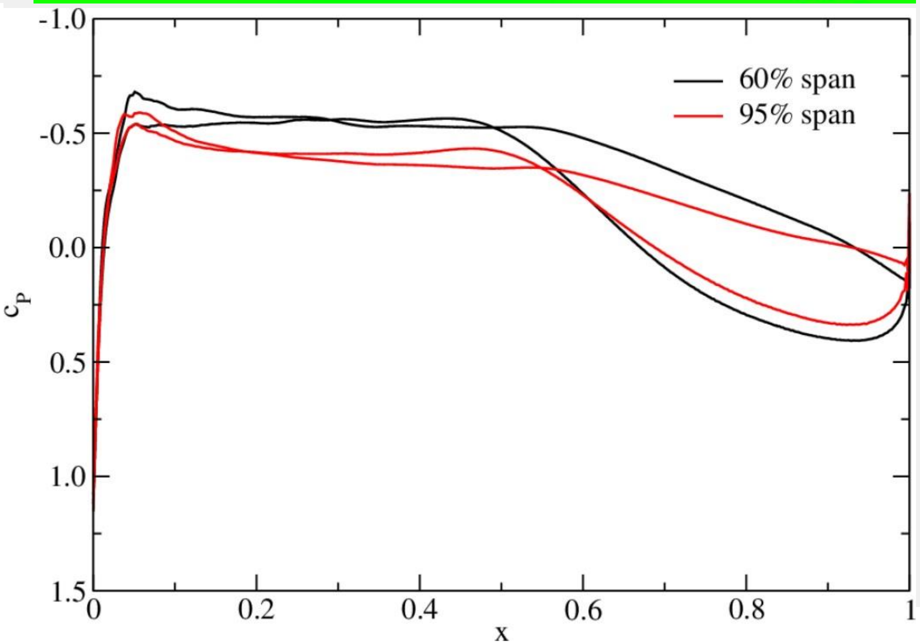


Mach 0.74, $\alpha = 0^o$

- Subsonic inflow conditions
- Flutter case







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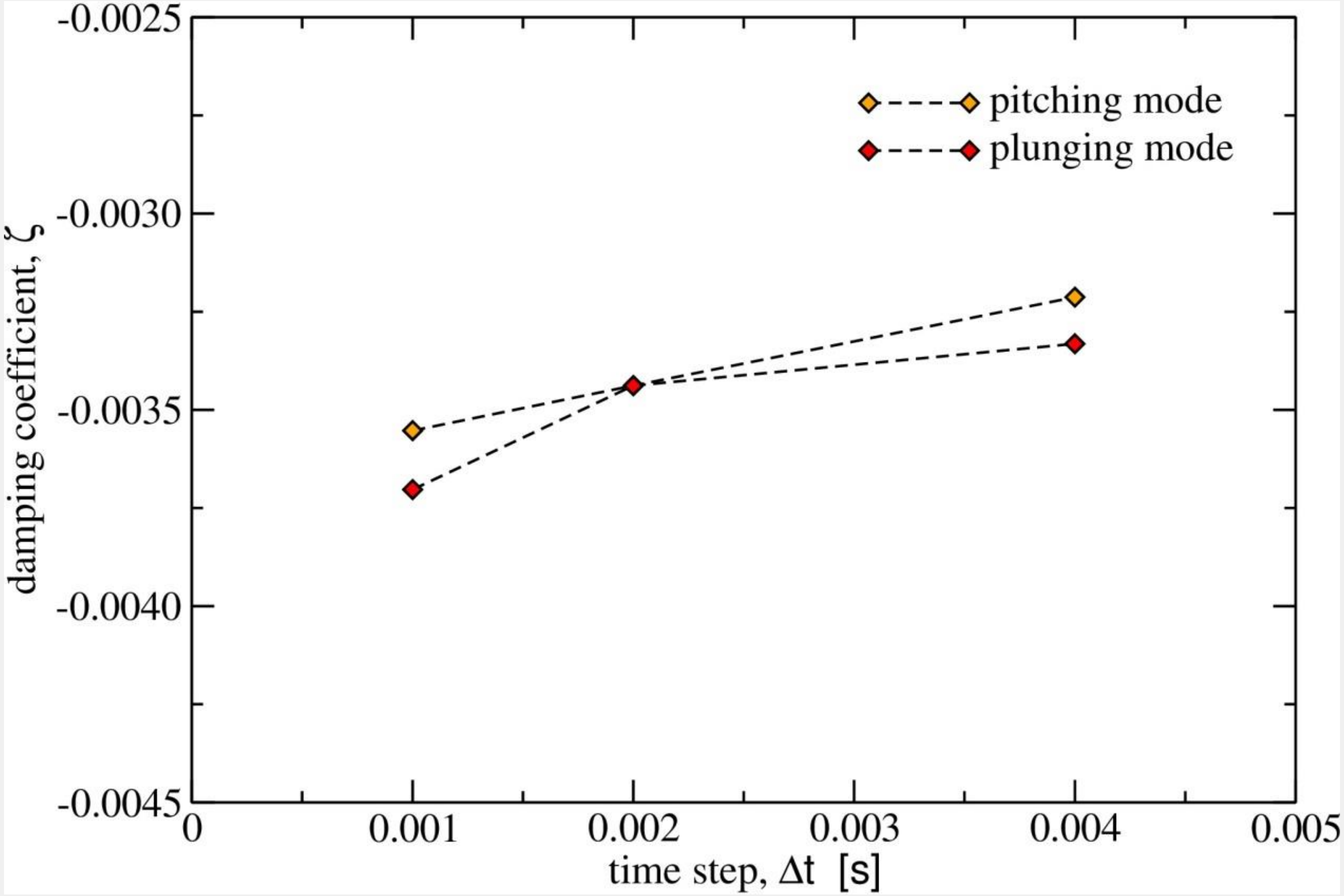
Time Step Study – Strong Coupling

- On sub-iteration level – strongly coupled scheme
- Nominal time step is $\Delta t = 0.002$ seconds
- Number of sub-iterations
  - From about 20 sub-iterations the result is becoming independent, we have used 30 for this time step.
  - Reduction in residuals approximately 2.5 orders of magnitude
  - For other time step the number of inner iterations set so that the reduction in residual is around 2.5 orders of magnitude

Time Step Study – Strong Coupling

- Damping coefficient for pitching and plunging mode
- The two damping coefficients are in the same order



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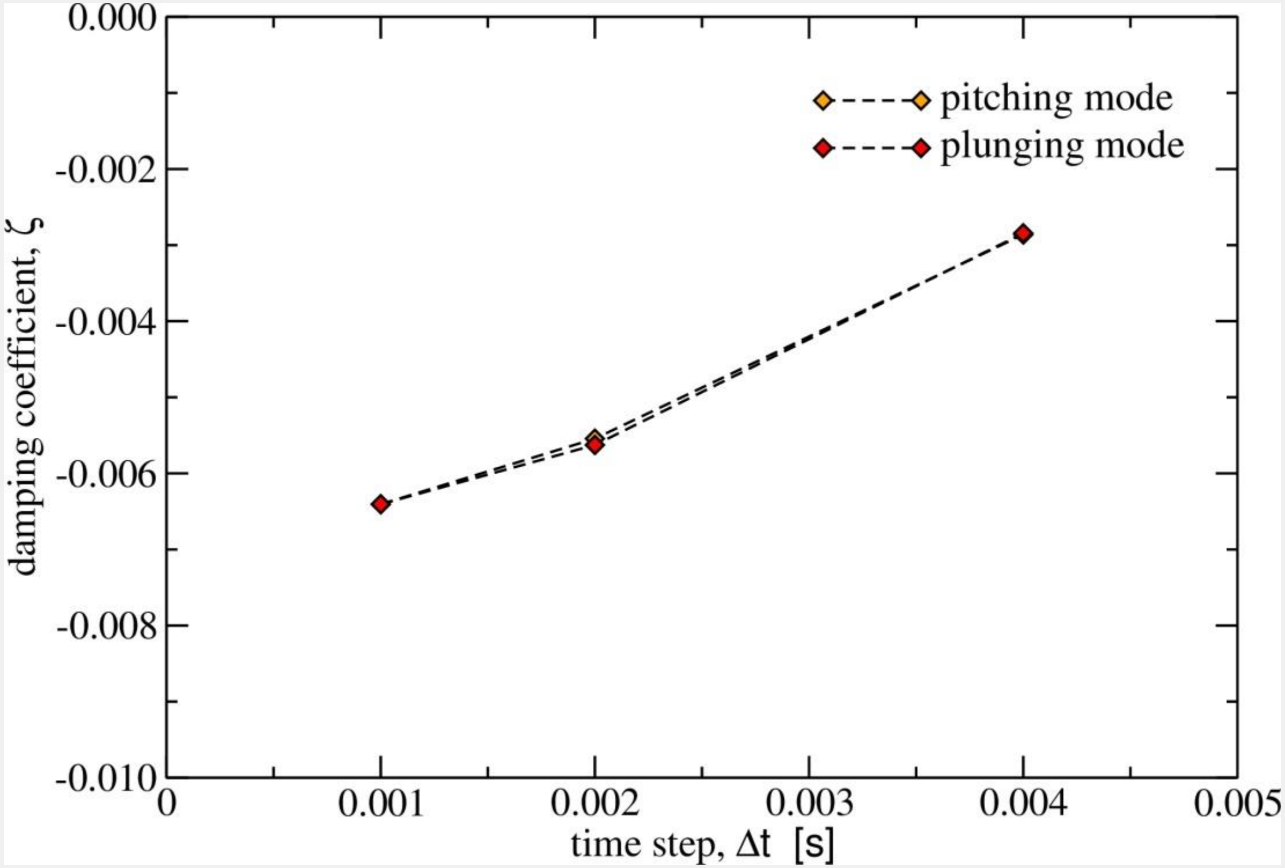
Time Step Study – Weak Coupling

- Damping coefficient for pitching and plunging mode
  - The time step and reduction of residuals in each time step is the same as the in the strong coupled scheme simulation
- The two modes have equal damping



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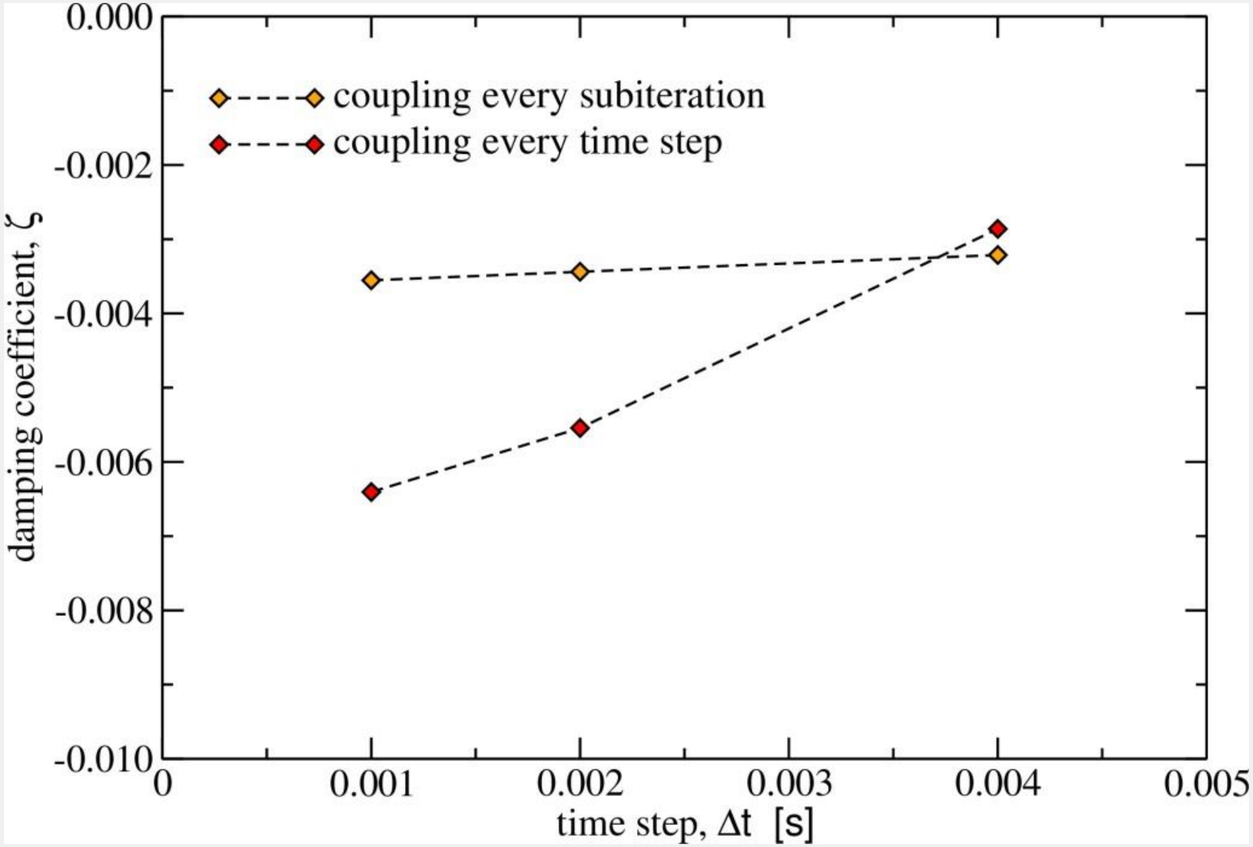
Strong vs. Weak Coupling Time Steps

- Strong coupled scheme shows a much smaller dependency of the result on time step
- Weak coupled scheme does not have unique solution



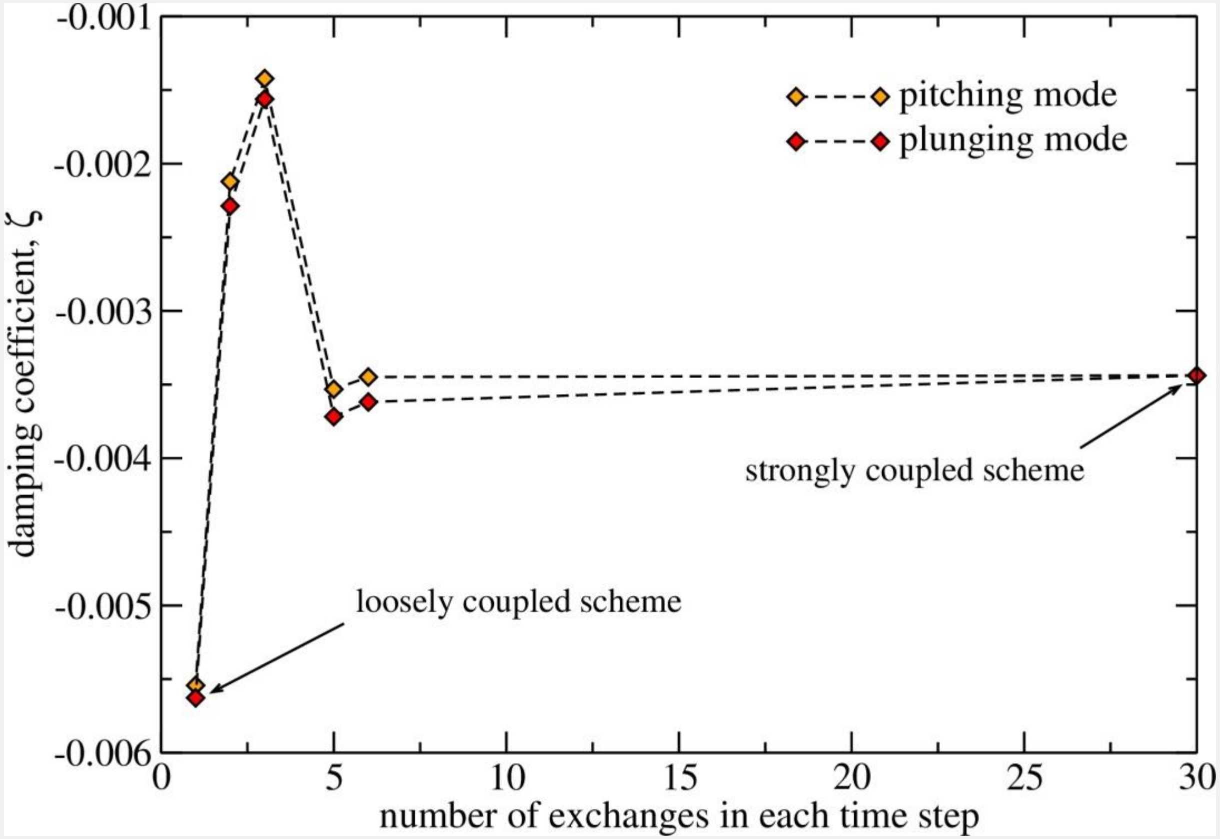
Weakening the Strongly Coupled Scheme

In the following the possibility to reduce the number of time synchronizations each time step is investigated?

- Reduced computational time, in particularly due to the reduced time spent on mesh deformation
- The starting nominal strongly coupled scheme uses
  - 30 sub-iterations
  - and 30 time synchronization each physical time step (every sub-iteration)

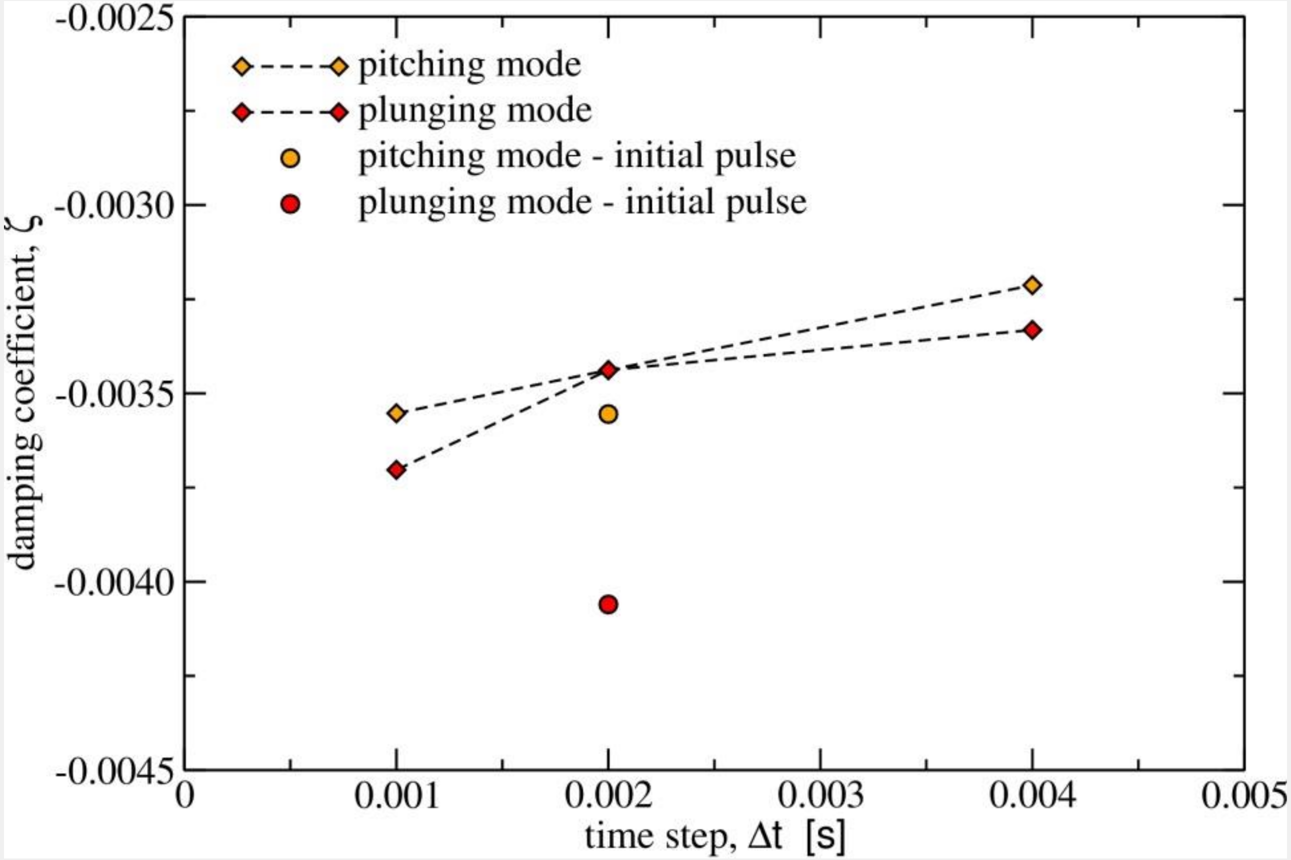
Weakening the Strongly Coupled Scheme

- Above five exchanges per time step the results start to be independent of the number
- This is similarity to static aeroelasticity where common practice is to perform five loops to get converged solution



Damping Comparison on Initial Pulse

- The wing is released from the rigid “jig” shape
- Initial pulse with the first step prescribed as a 0.1 m plunge and 1° pitch



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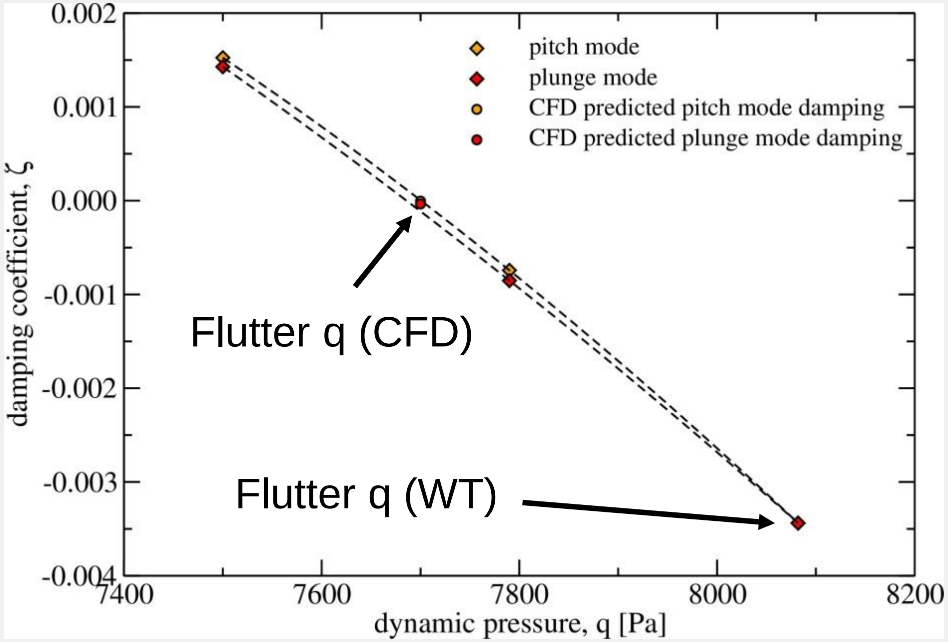
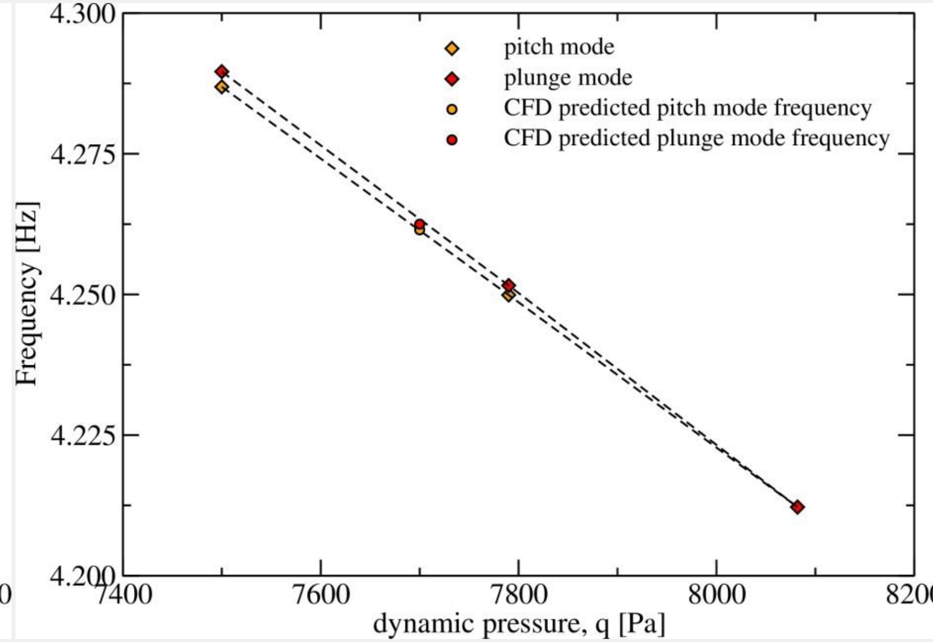
Estimated Flutter Dynamic Pressure

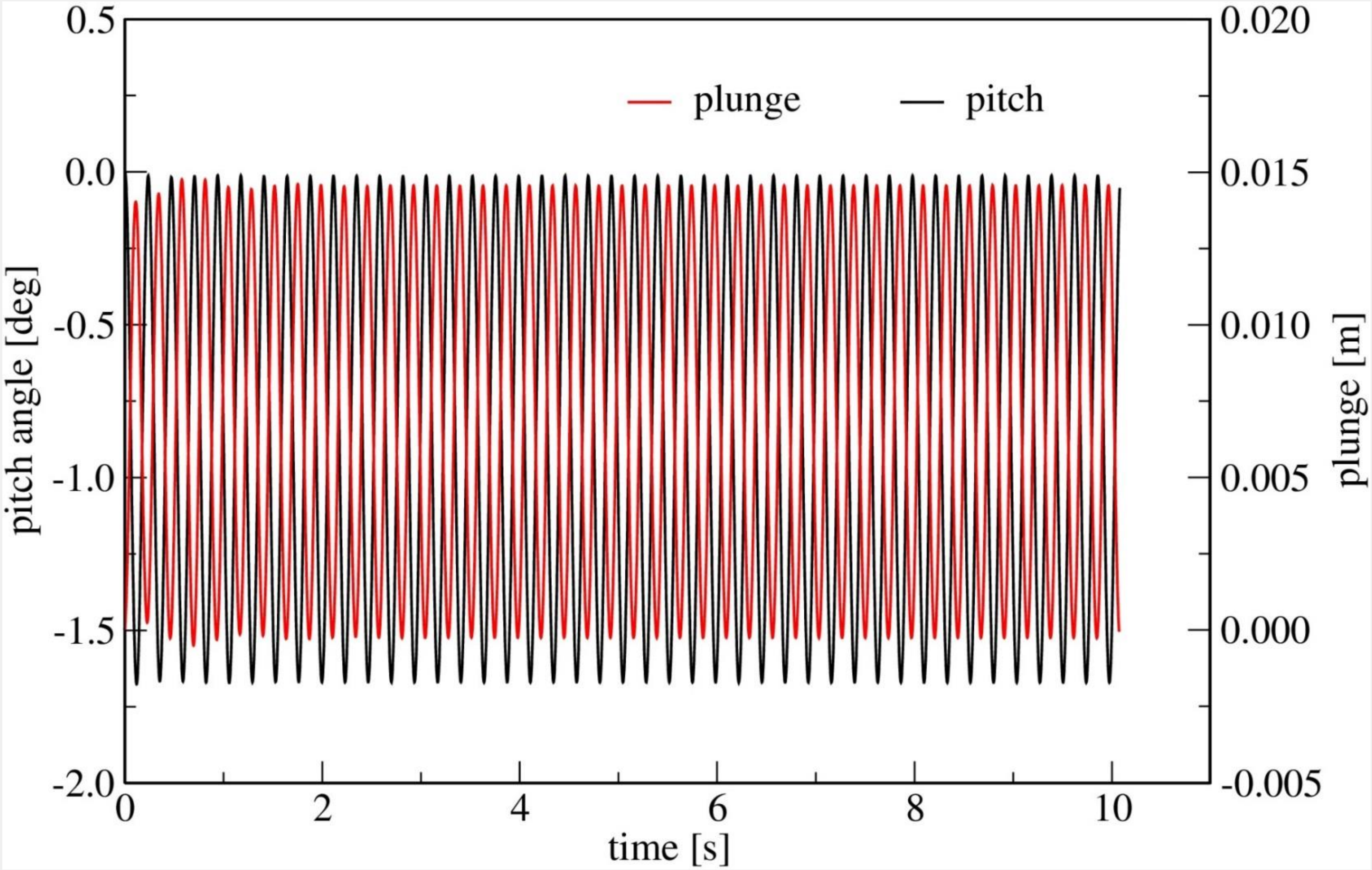




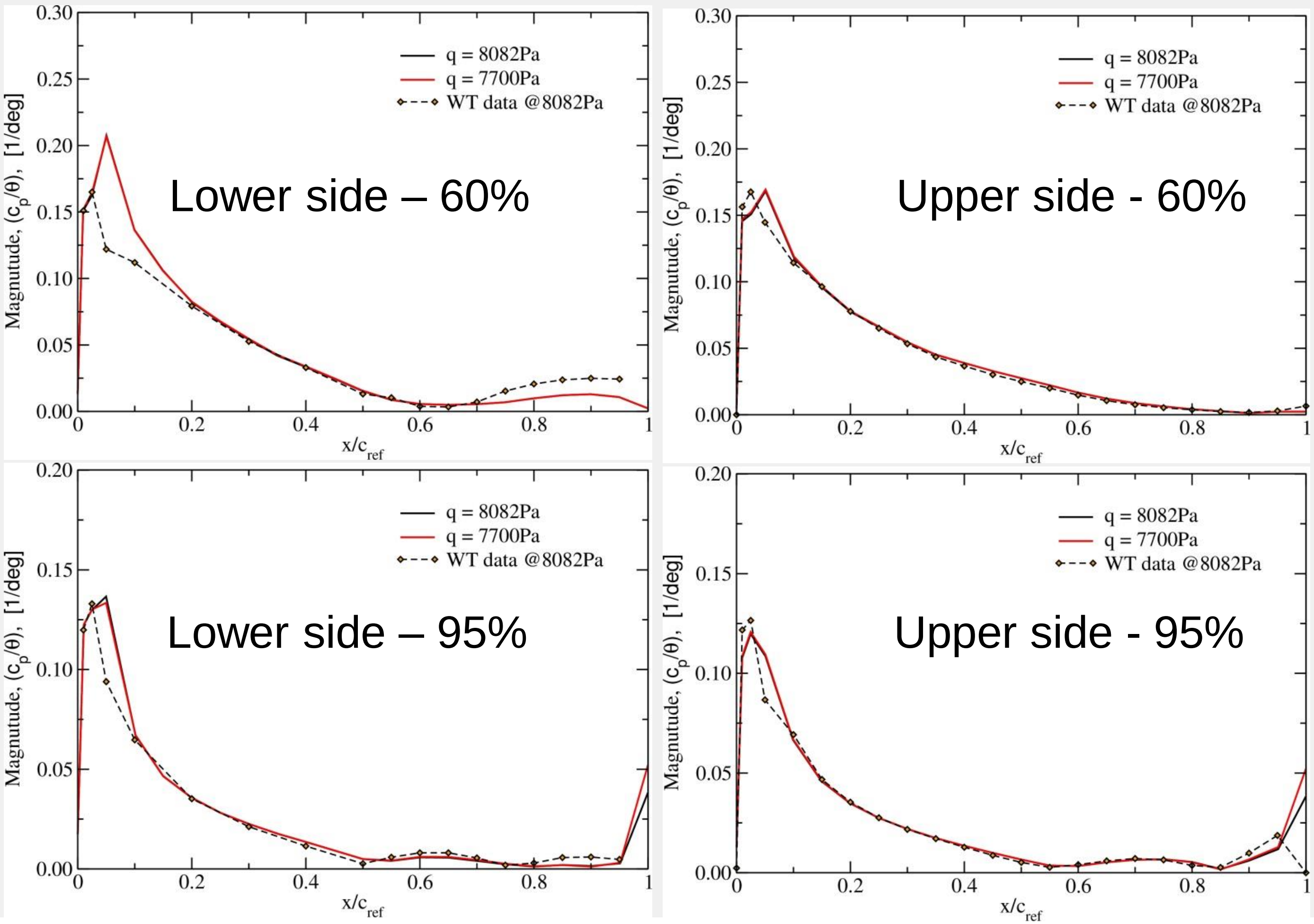
Three different dynamic pressures calculated

- The estimated CFD flutter dynamic pressure is 7700 Pa
- WT flutter dynamic pressure is estimated at 8082 Pa
- With WT measured flutter frequency at 4.3 Hz and for CFD 4.26 Hz

Modal Coordinates at Flutter Dynamic Pressure



FRF Magnitude Comparison



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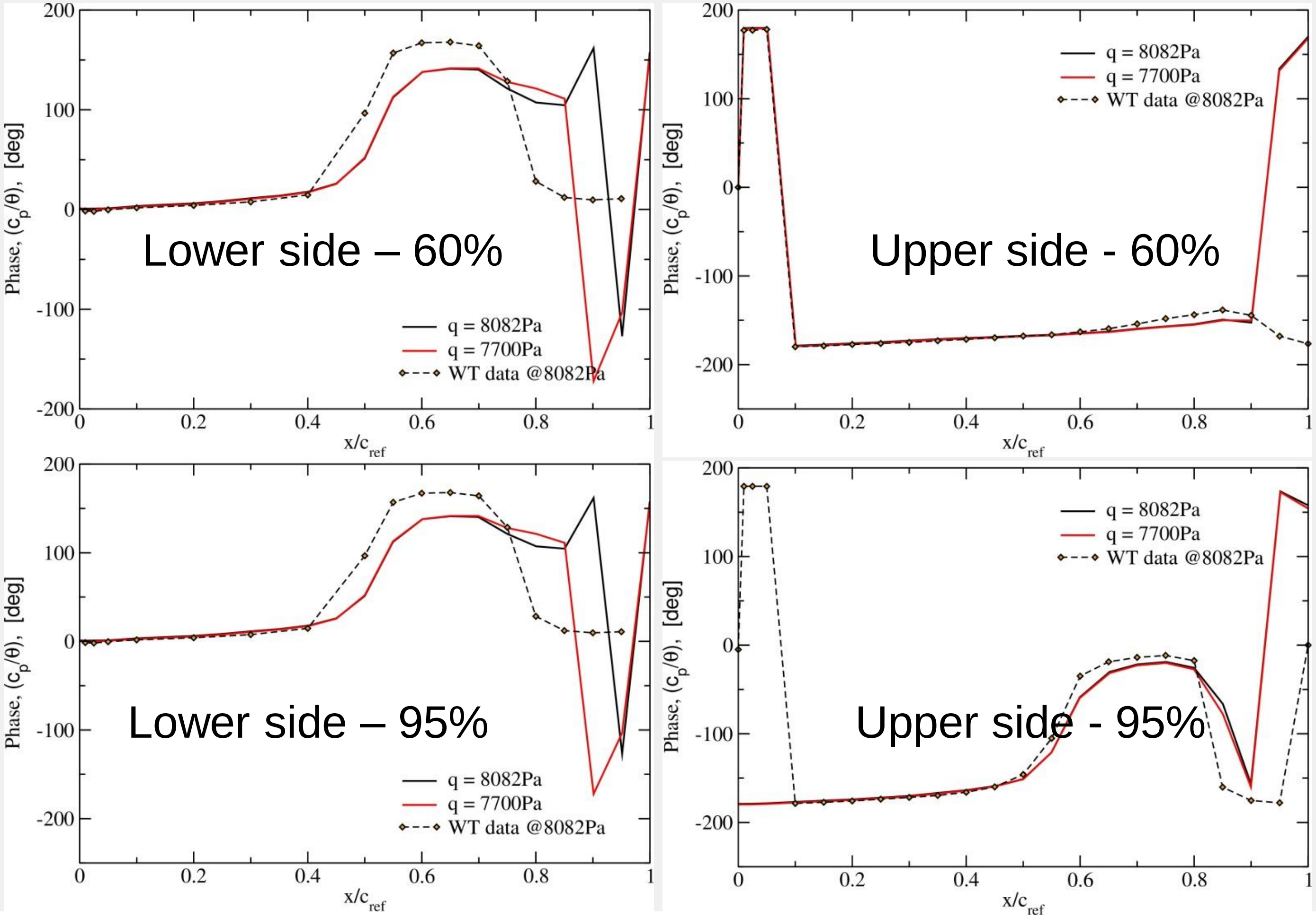
FRF Phase Comparison



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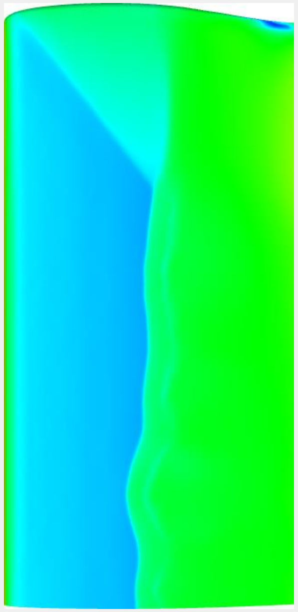
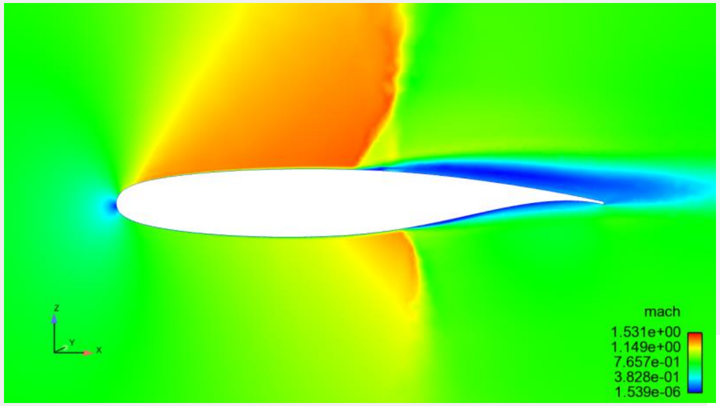
Case 3: Mach 0.85 and $\alpha = 5^{o}$

Unsteady CFD solution

- URANS-SA – averaged solution

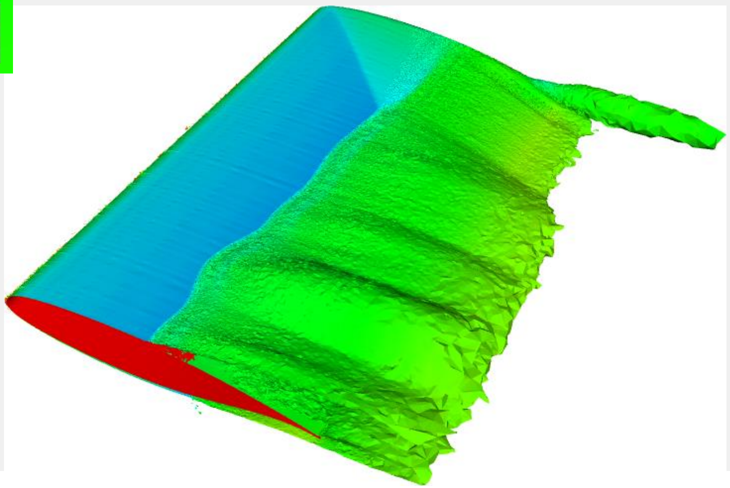


Pressure on the surface



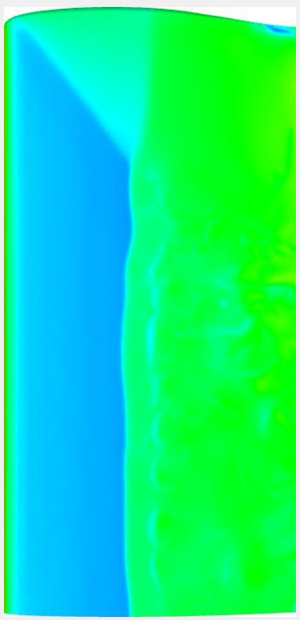
Mach number in the plane where the c_p is collected

Vorticity colored by c_p

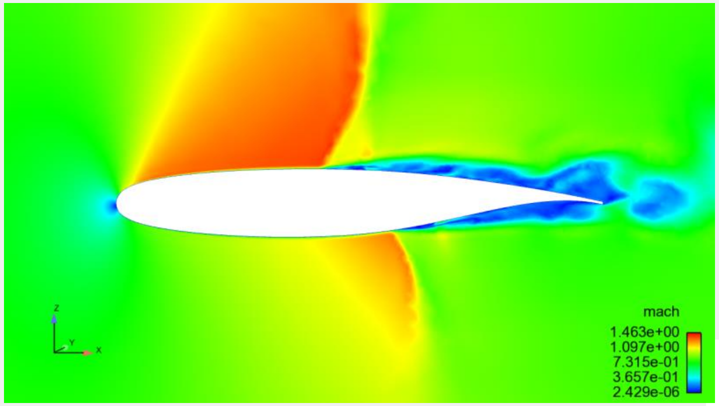


Unsteady CFD solution

- Hyb0 – snapshot at one time step



Pressure on the surface



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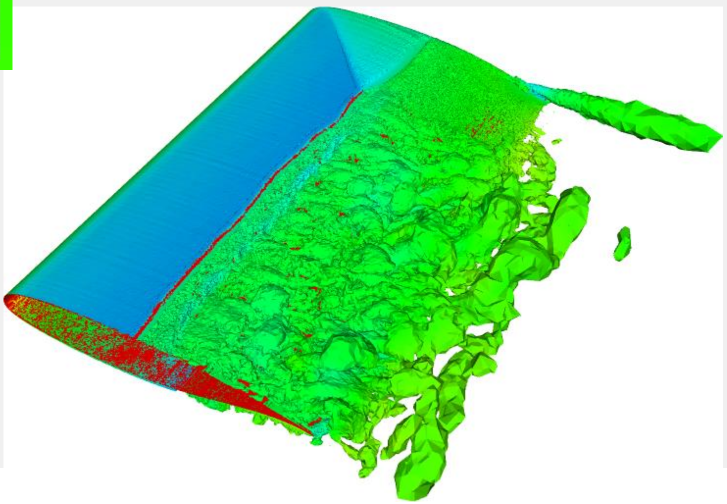
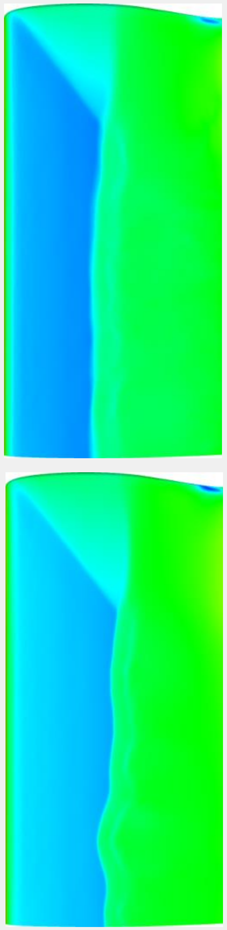
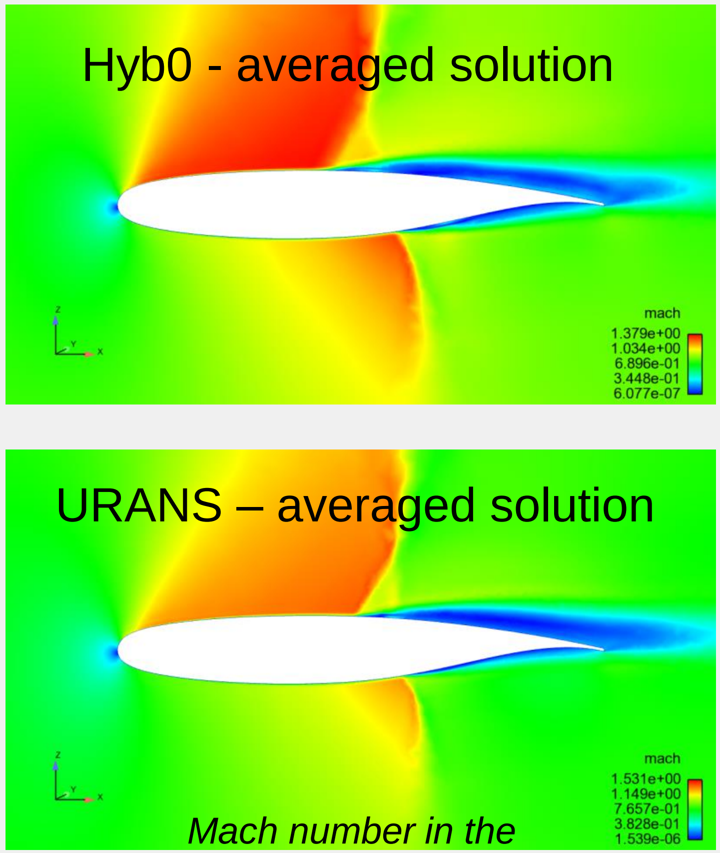


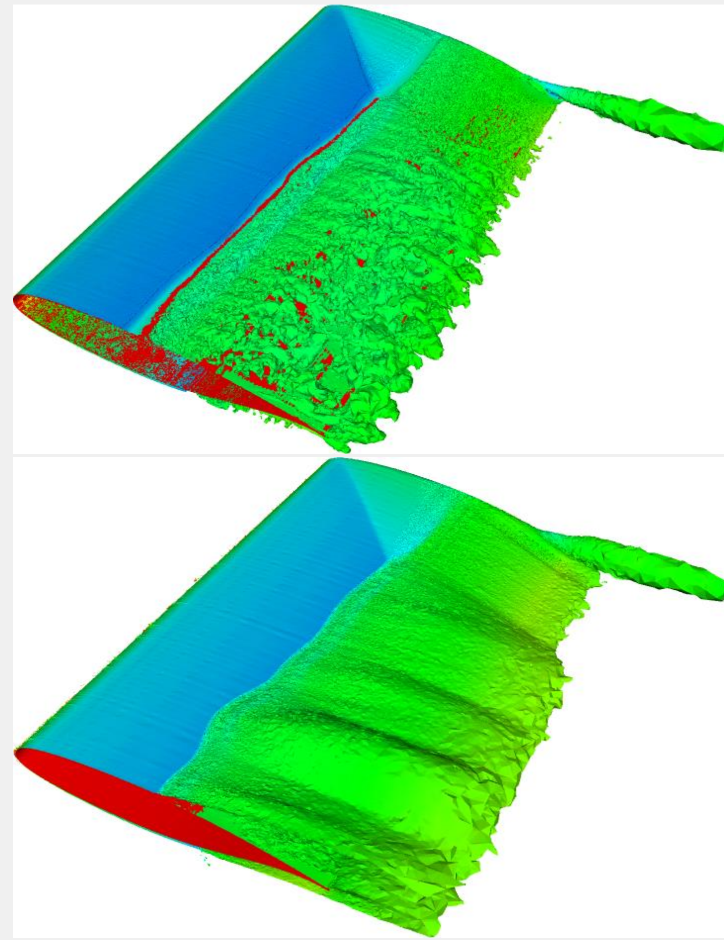
Unsteady CFD solution



Pressure on the surface

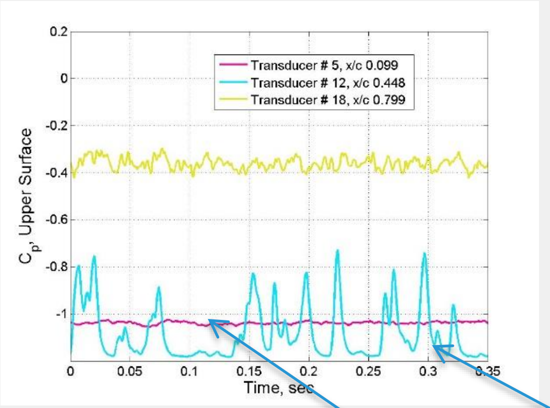


Mach number in the plane where the c_p is collected

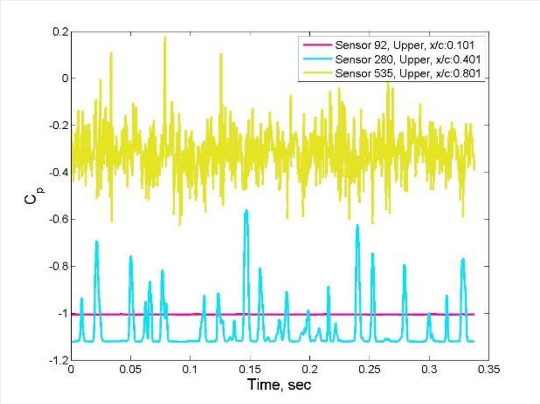


Vorticity colored by c_p

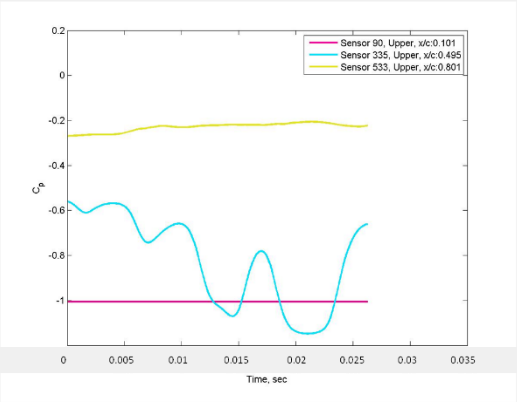
C_p time histories in regions 1-3



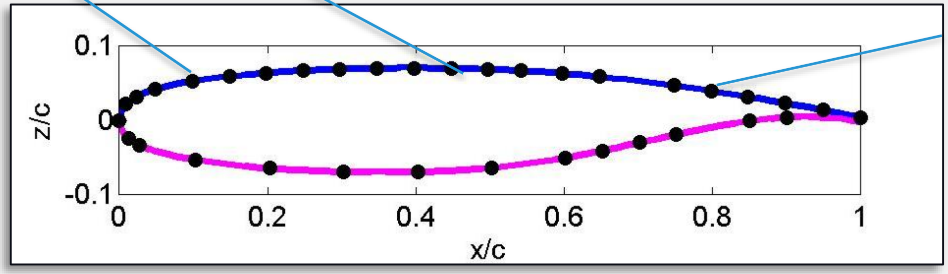
Experiments



Hybrid RANS-LES



URANS

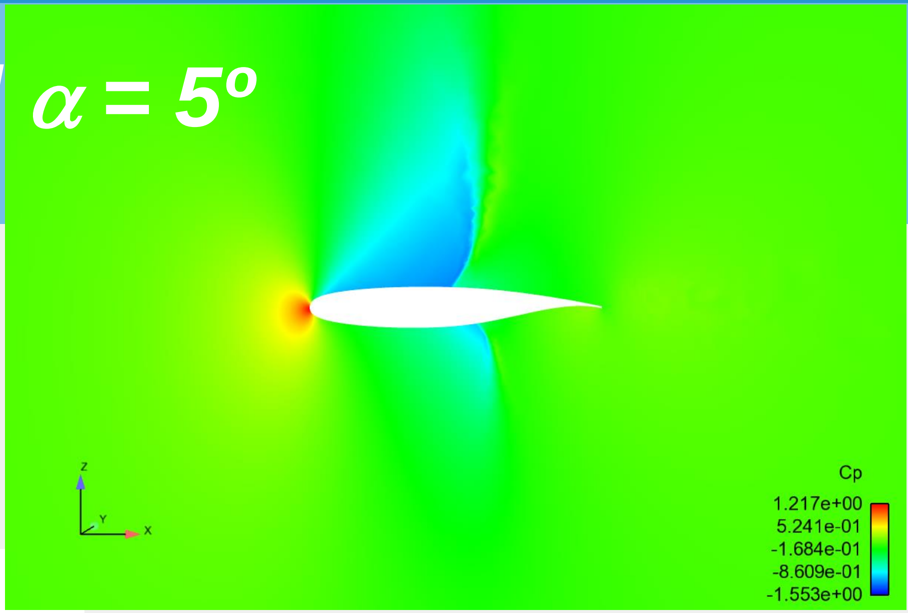


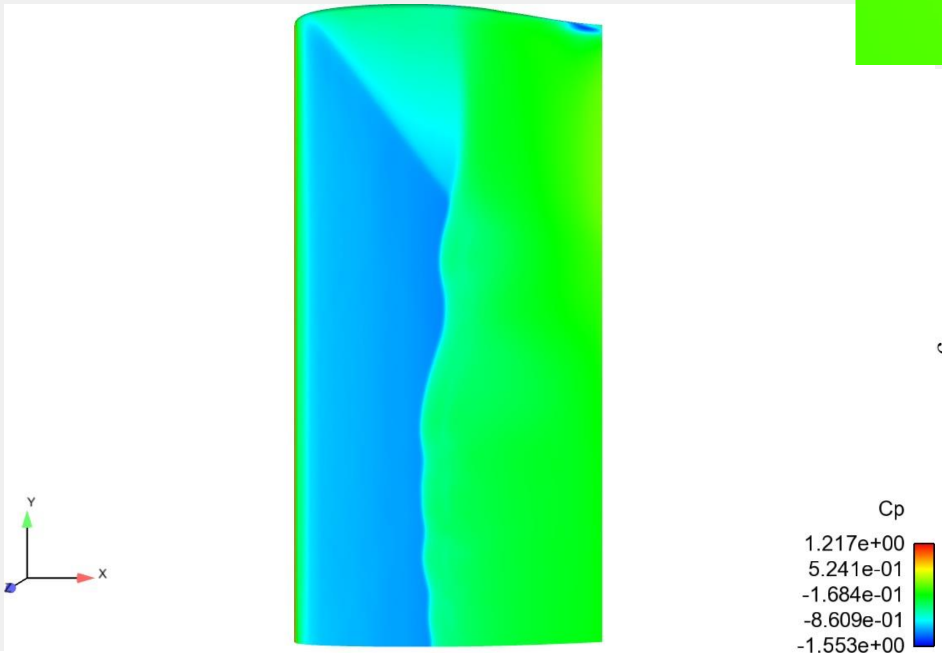
Transducer # 18

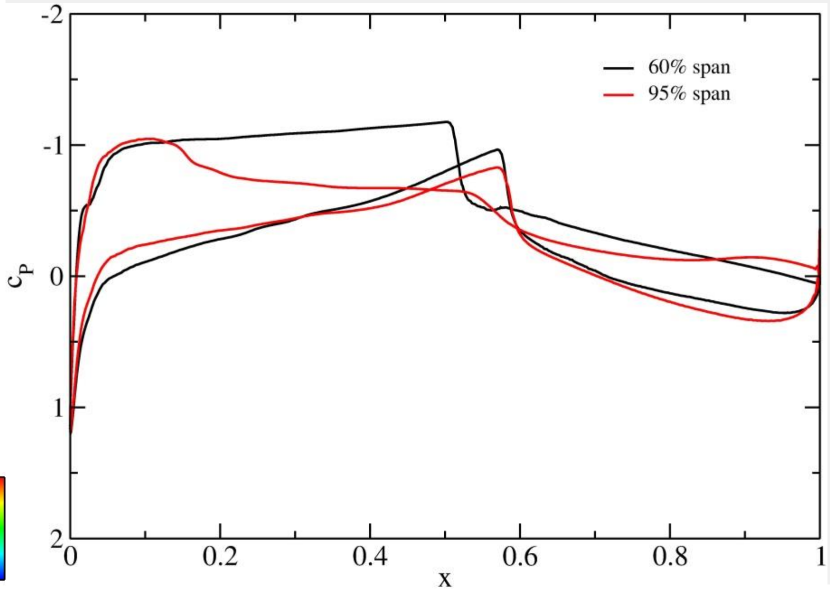
1) Ahead of shock region x/c<0.3736 (magenta line)
2) Shock region (0.3736<x/c<0.4750) (blue line)
3) Aft shock region x/c>0.4750 (yellow line)

Case 3: Mach 0.85 and $\alpha = 5^o$

- Transonic flow
  - SA model
  - Do not see any large separation

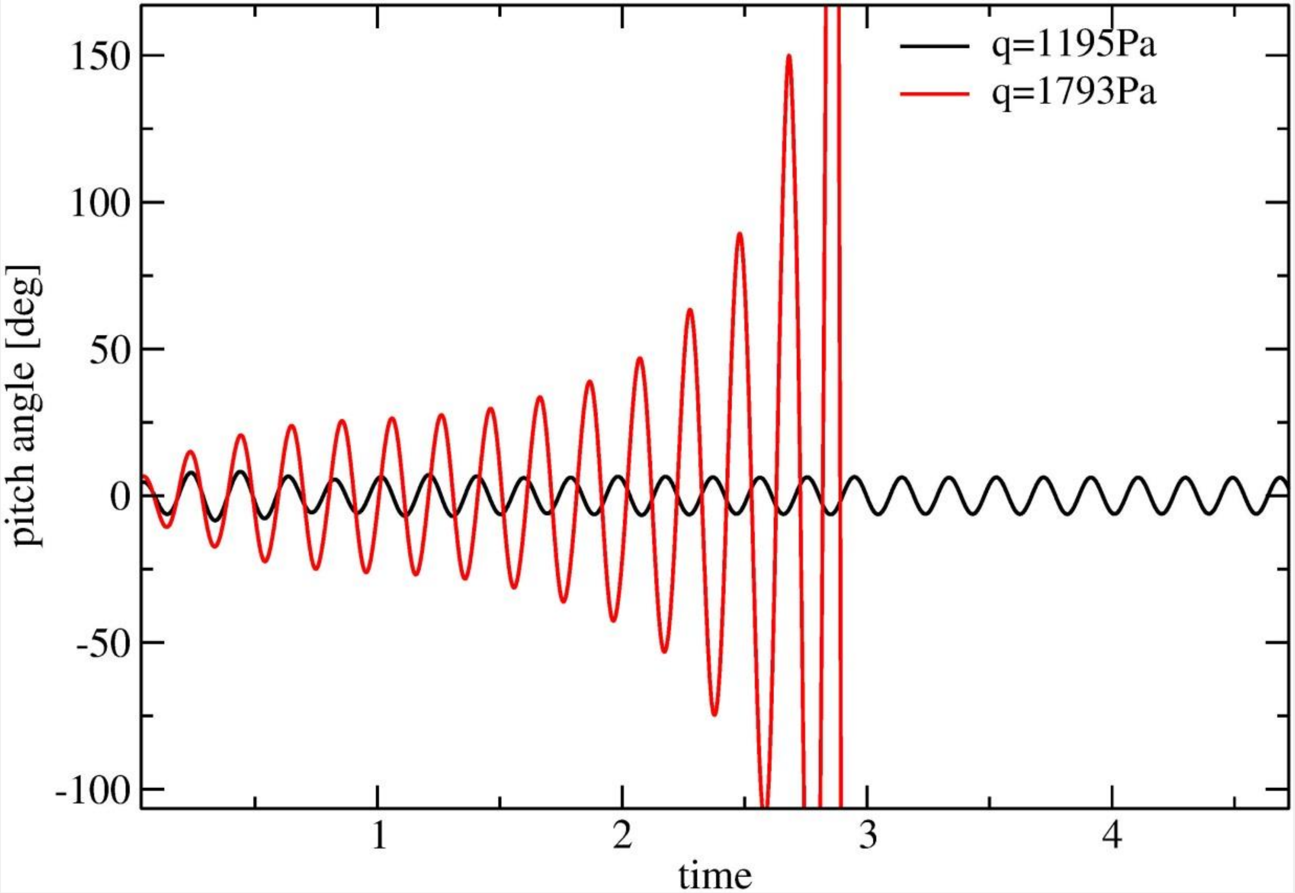






Different Dynamic Pressures

- Calculated at five different dynamic pressures
  - The flutter dynamic pressure ~25psf



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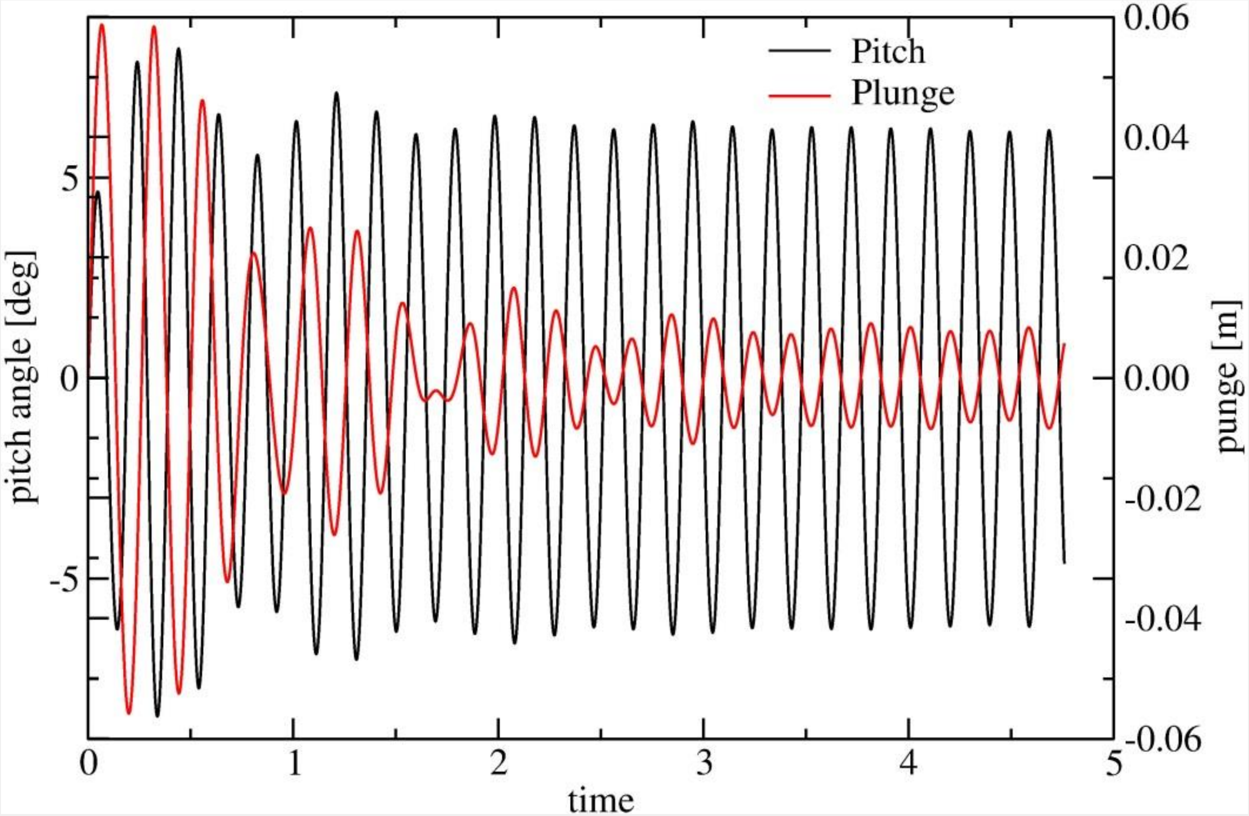
Pitch and plunge @ flutter pressure

- Damping coefficients and frequency
  - Initial 3 seconds - transient
  - Pitching mode: ζ=0.00031, f=5.18Hz
  - Plunging mode: ζ=0.00017, f=5.18Hz



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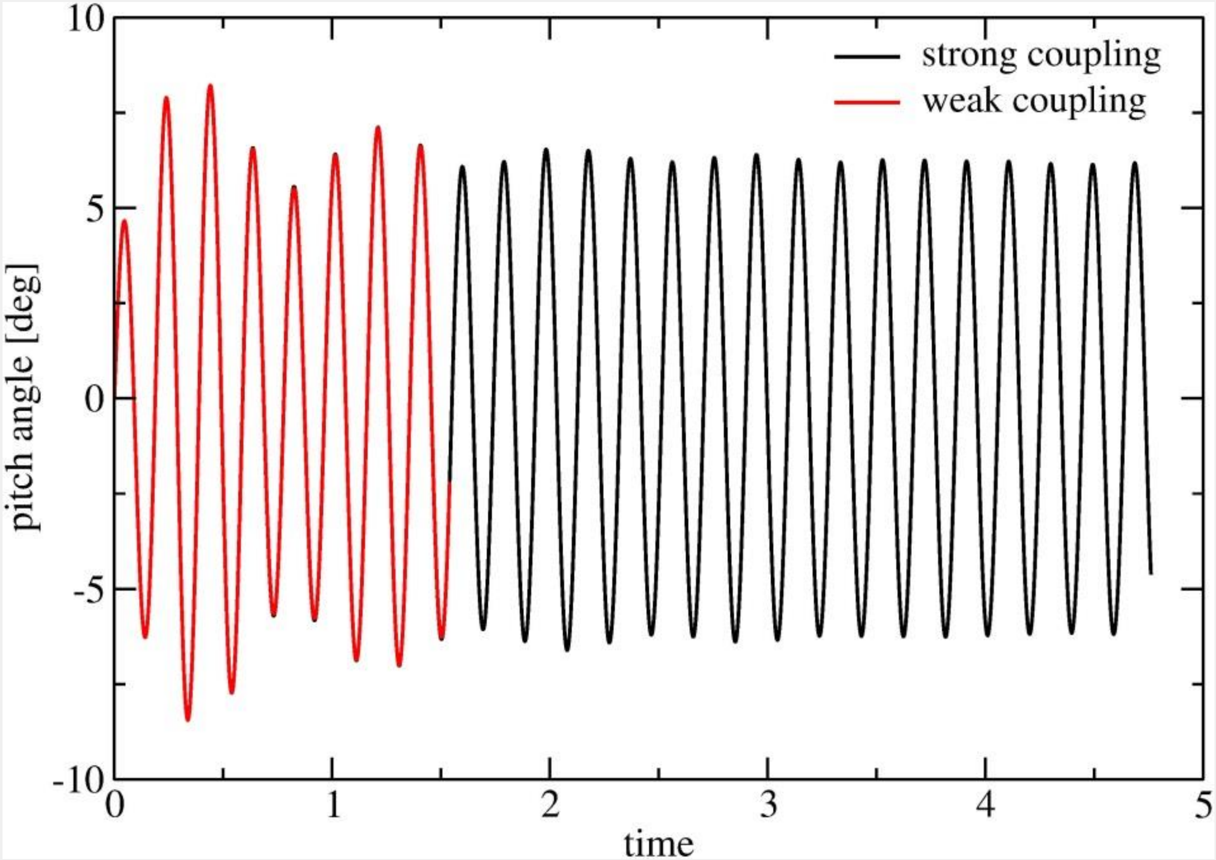
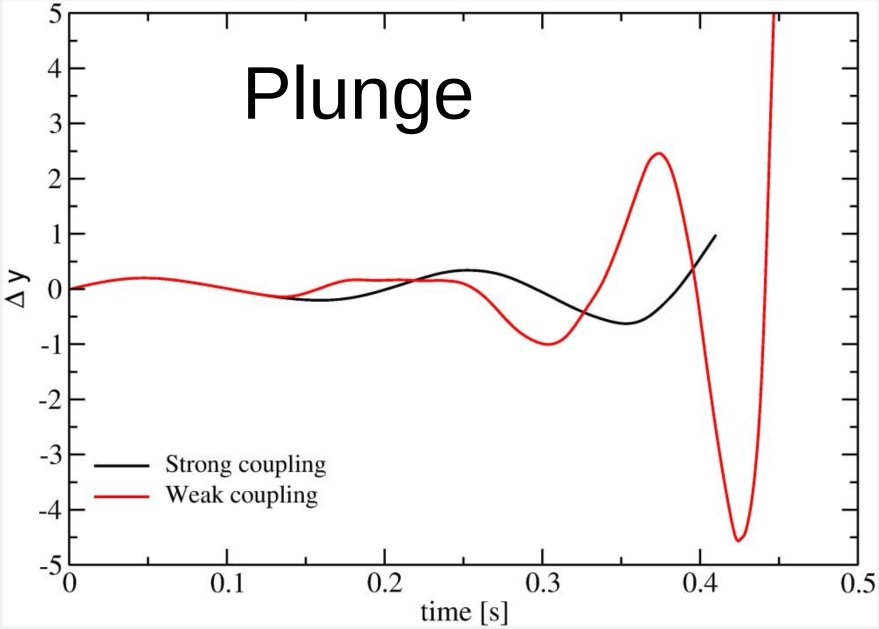
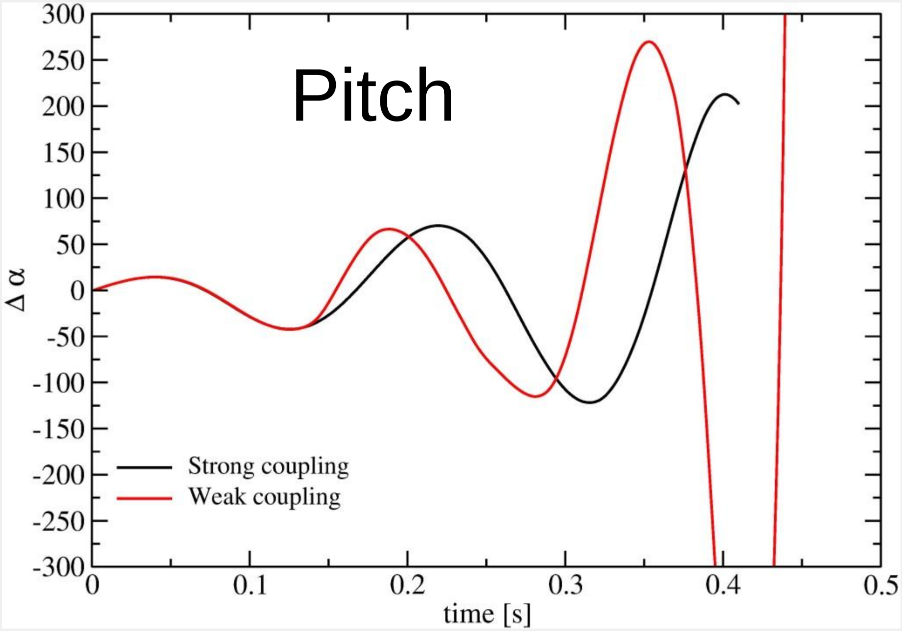
Weak vs. Strong Coupling

- Surprisingly not as strong effect as for case M = 0.74 case (case 2)
  - Graphs show data for flutter dynamic pressure



Weak vs. Strong Coupling





- Test at Mach 0.85 and $\alpha = 0^o$
- Clear effect of the type of coupling used in this case

Conclusion

- The dominant effect for this case is coupling
  - There is no flow separation, the flow is linear of weakly non-linear
  - Structure is linear
  - Allow for larger time steps
    - Provided the time integration of coupled system is of sufficient accuracy (second order)
- The above conclusion does not have to be necessarily valid for separated flow where the time scale is then determined by the flow separation modeling

For more detailes see separate AIAA paper:

A. Jirasek, M. Dalenbring and J. Navratil, *Numertical Study of Benchmark Super-Critical Wing at Flutter Conditions*, AIAA SciTech 2016, 4-8 Jaunuary, San Diego, USA.