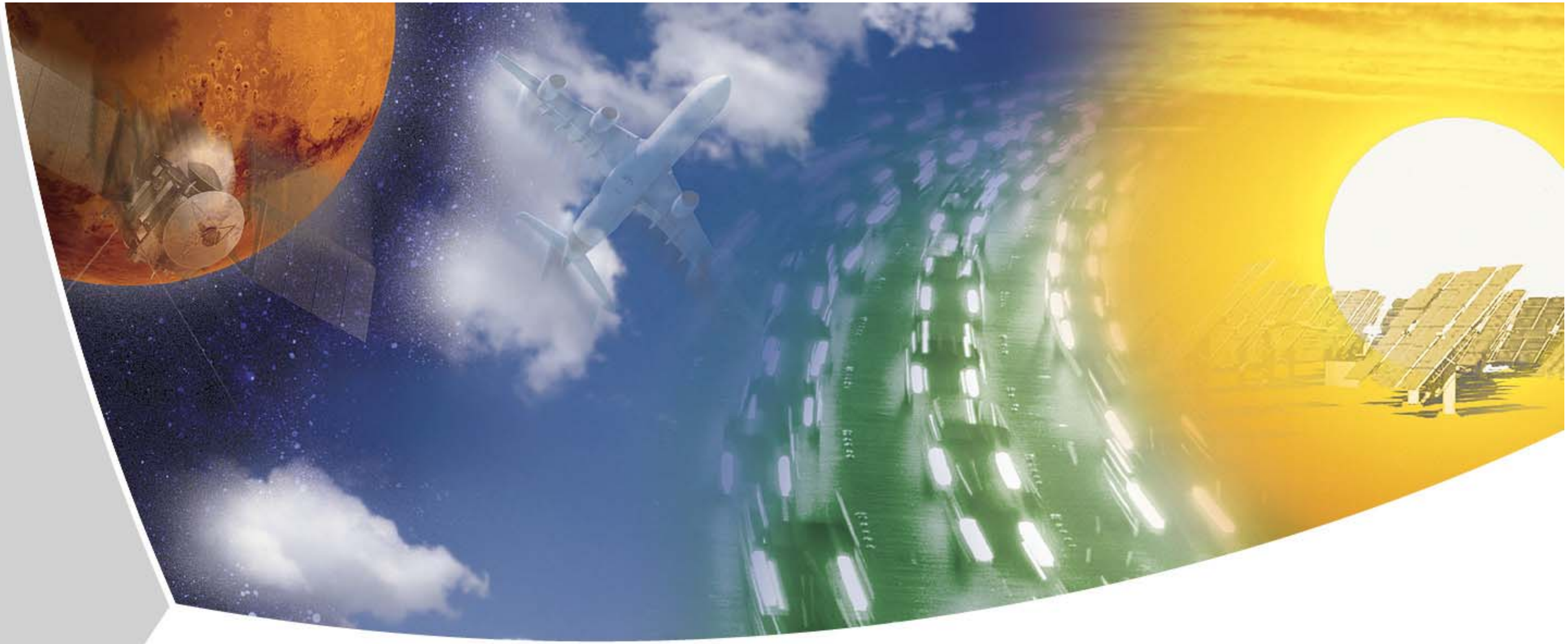

Current Activities in Numerical Unsteady Aerodynamics for Flutter- and Loads Analysis of Transport Aircraft

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Contents

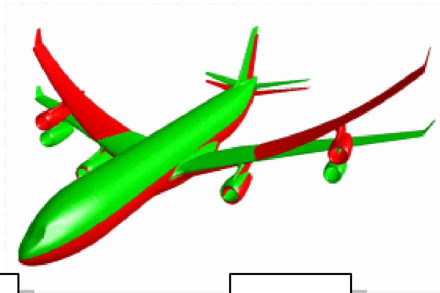
Overview: Types of Unsteady Aerodynamic Problems

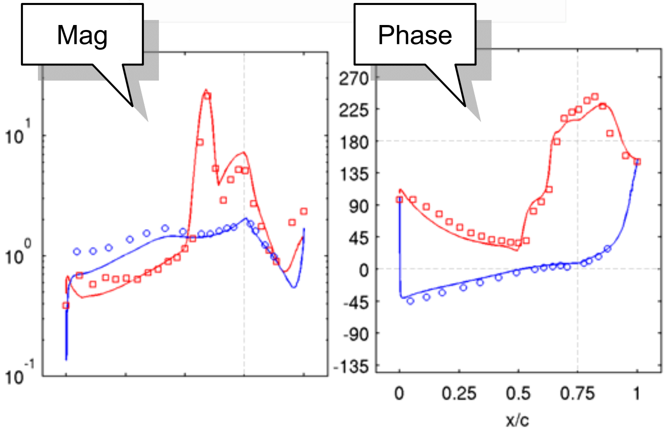
unsteady airloads

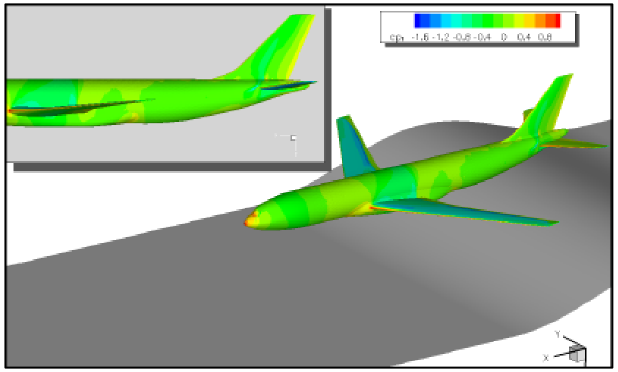
Motion-induced
(Flutter)

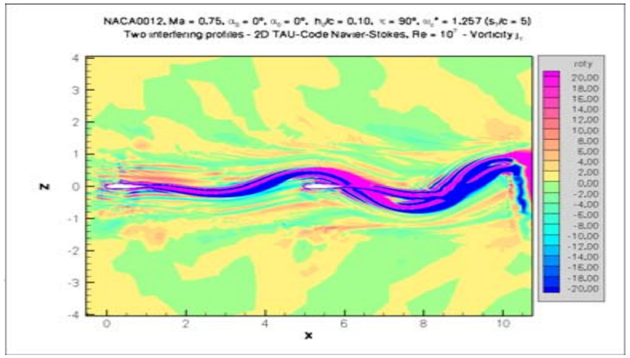
Dymamic response
(wakes, gusts)

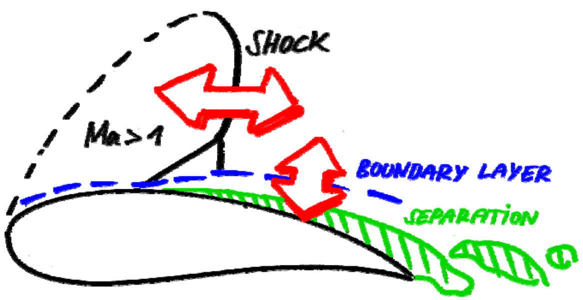
Flow-induced
(separation, buffet)

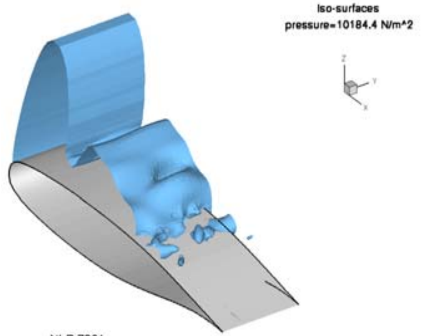






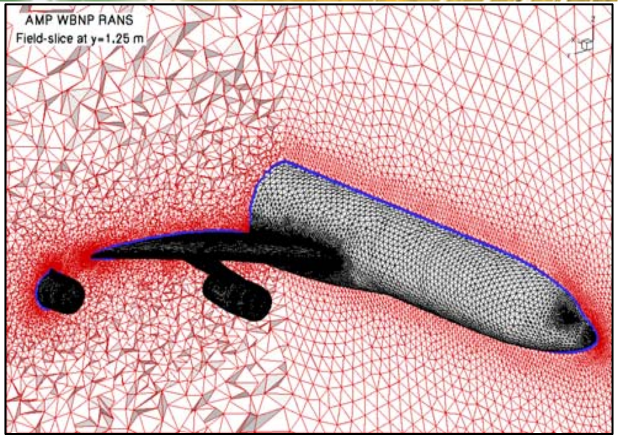


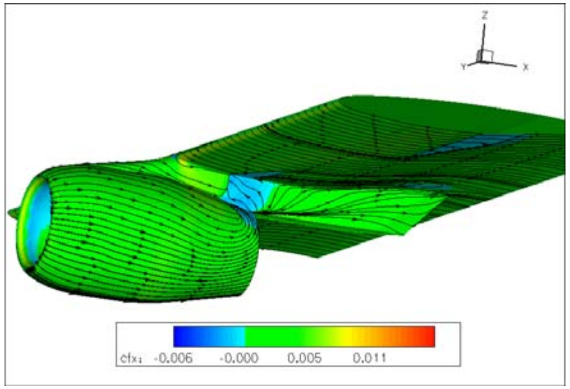


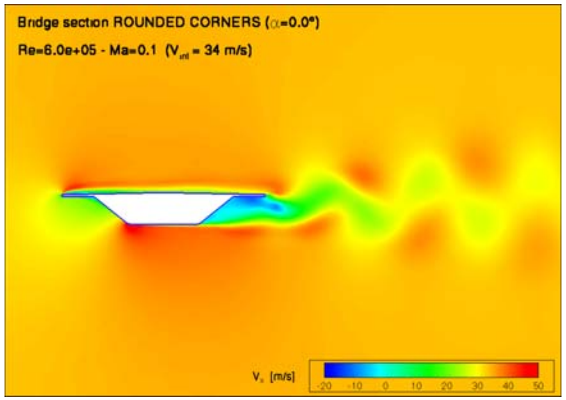


Main Tool: DLR's TAU-Code

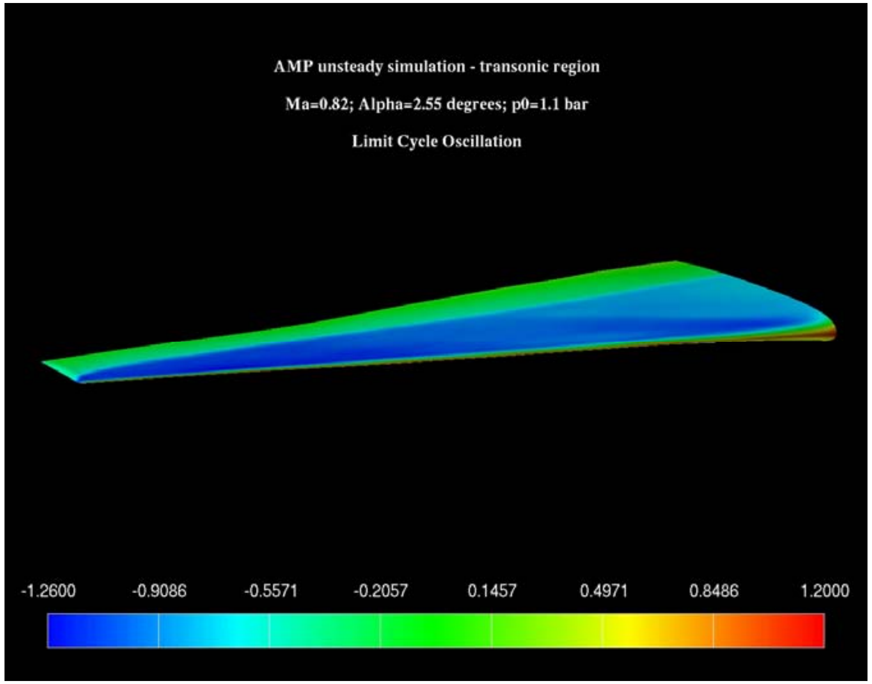
- 3D Finite Volume Scheme on unstructured hybrid grids (tetrahedra, prisms, pyramids, hexahedra),
- Integration of RANS- or Euler Equations
- 1-eq. , 2-eq- and RSM-turbulence models, DES
- Central or Upwind Spatial discretisation
- Time Integration by Explicit Multi-Step Runge-Kutta Scheme.
- Time Accuracy by Dual Time Stepping with Residual Smoothing for each Physical Time Step
- Local mesh adaptation: refinement/coarsening
- Chimera technique for overlapping grids
- High performance on parallel computers
- Efficient and robust Grid deformation tool
- Python-based fluid structure coupling







CFD Flutter Simulation



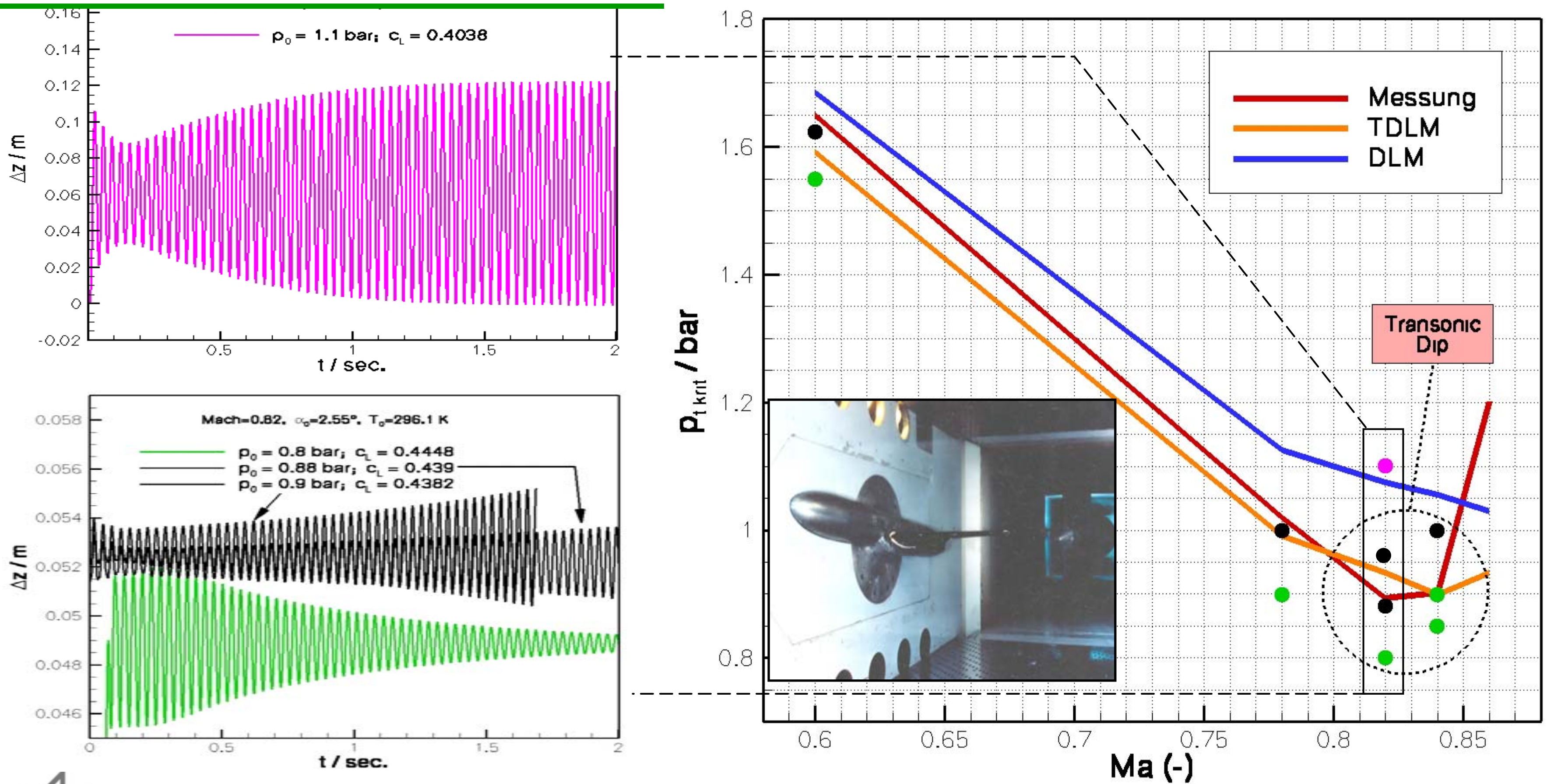
CFD Flutter Simulation

TAU-URANS – FEM coupling in time domain

$$[M]\{\ddot{u}\}+[D]\{\dot{u}\}+[K]\{u\}=\{f_a(u,\dot{u})\}=aero$$

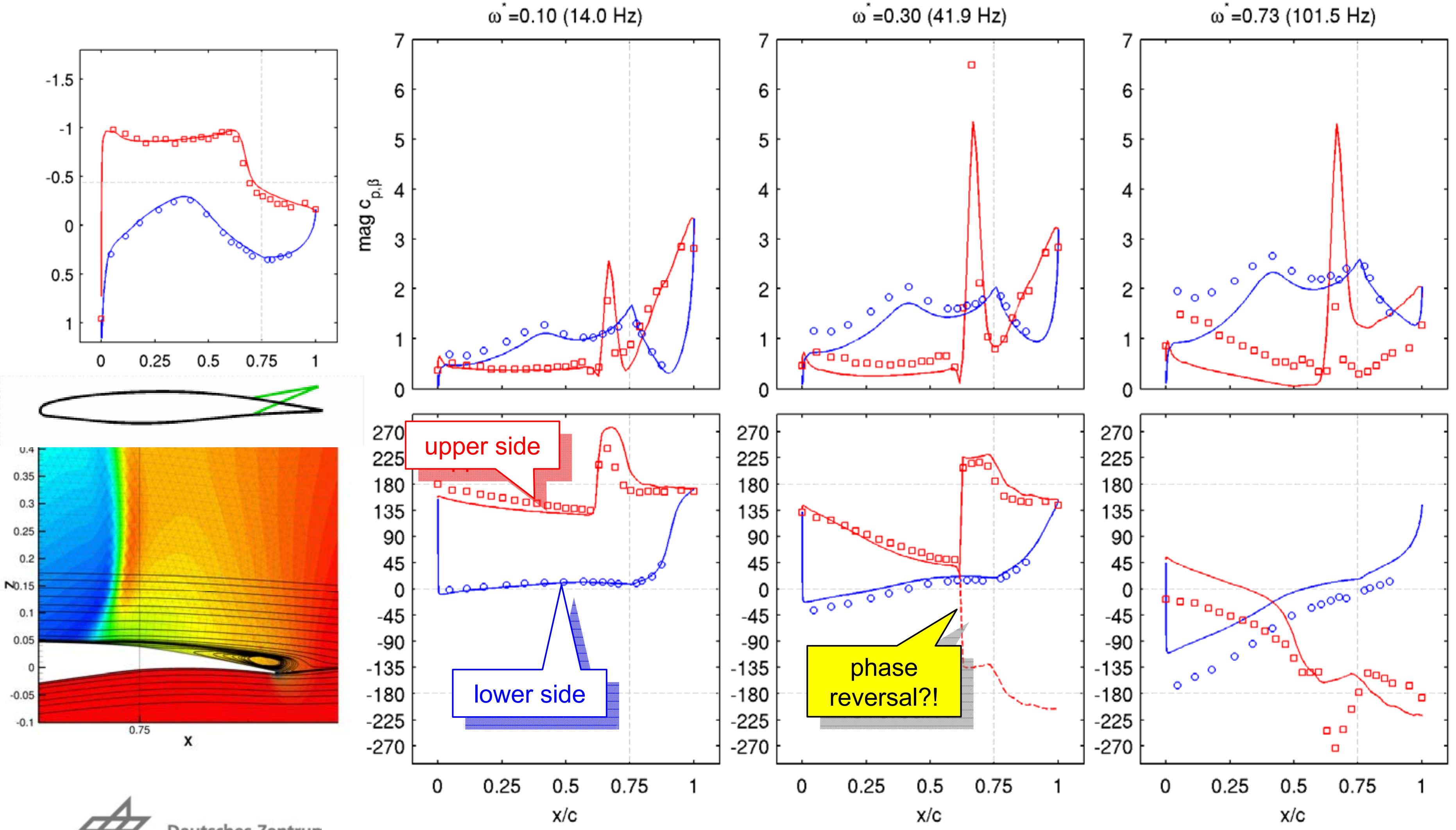
Eigenvalue problem in frequency domain TDLM-Aerodynamics

$$\left(-\omega^2\left[\bar{M}\right]+\left[\bar{K}\right]-q_\infty[Q]\right)\{\hat{q}_e\}=0$$

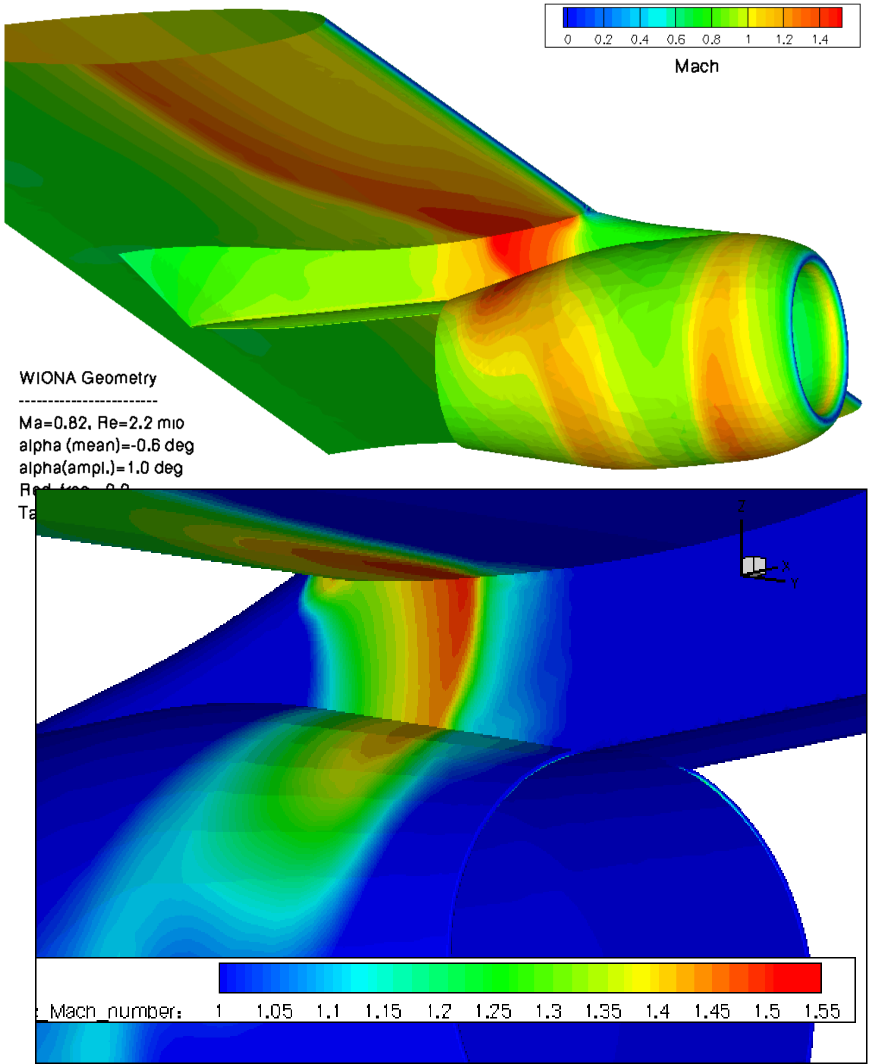


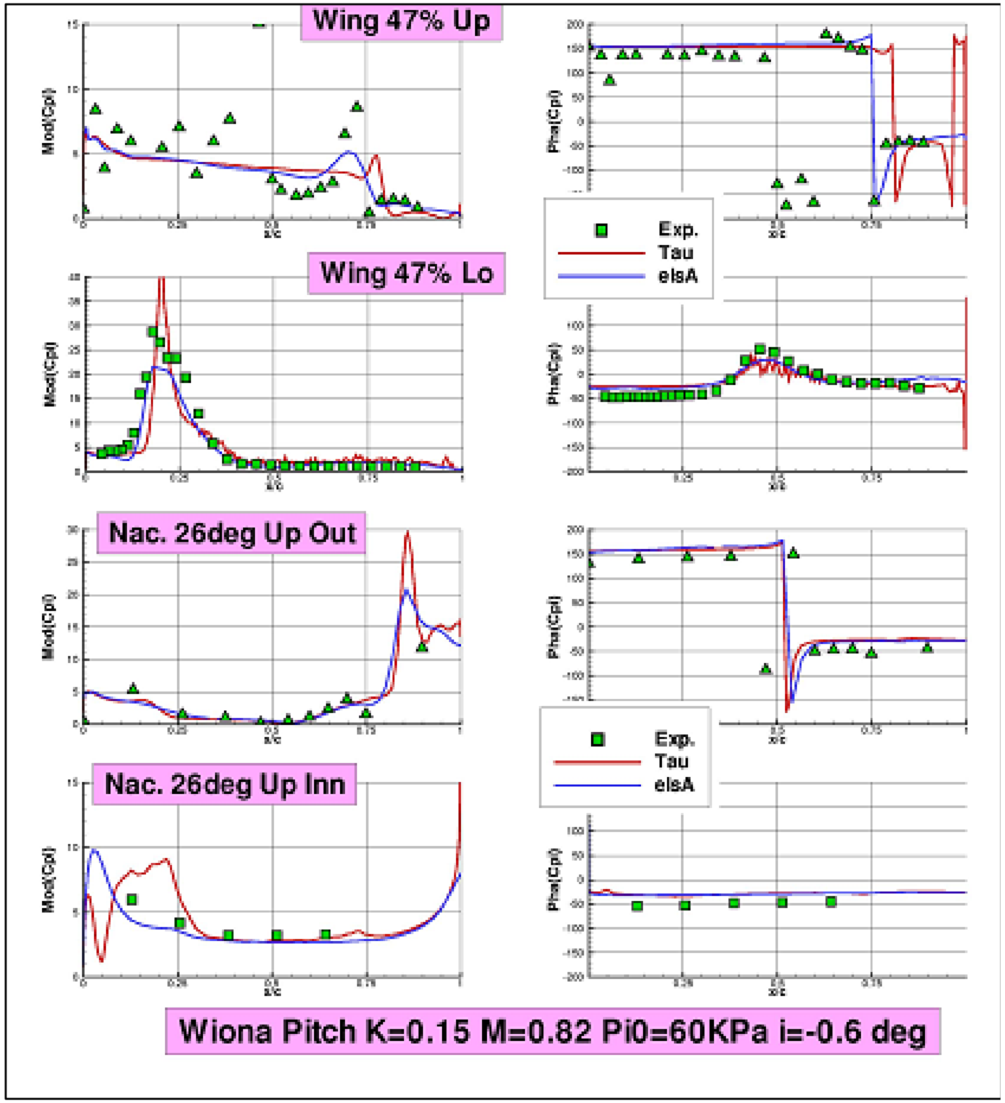
Validation: Unsteady Control Surface Aerodynamics

Shock and flow separation close to hinge axis, Ma=0.80, α_0=2°, β_0=2°



Validation: Wing-Pylon-Nacelle Interferemce (WIONA)



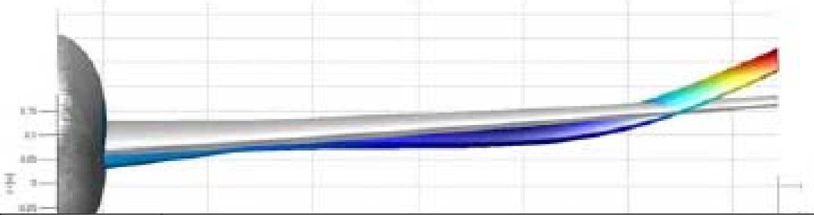


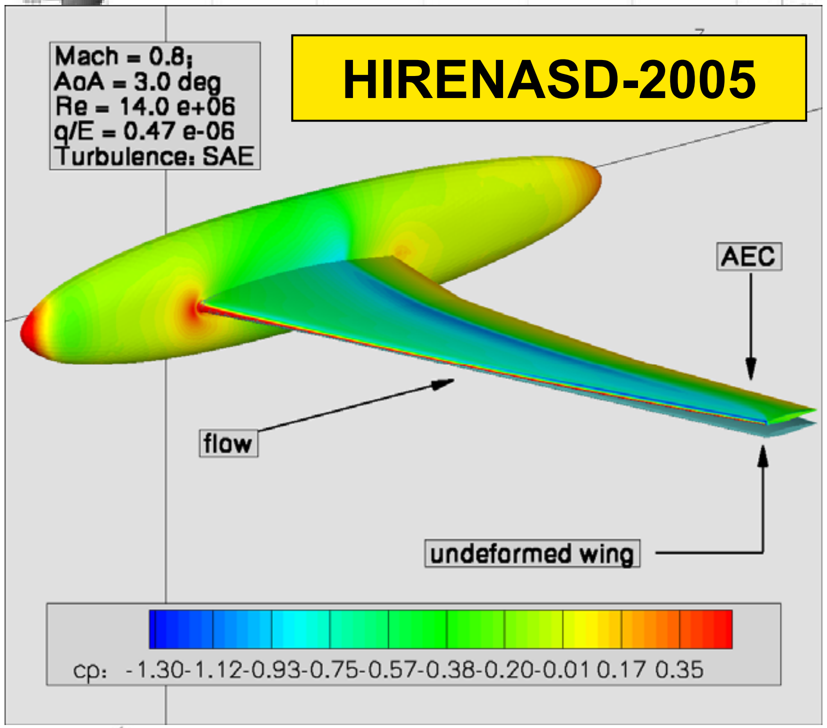
Validation HIRENASD

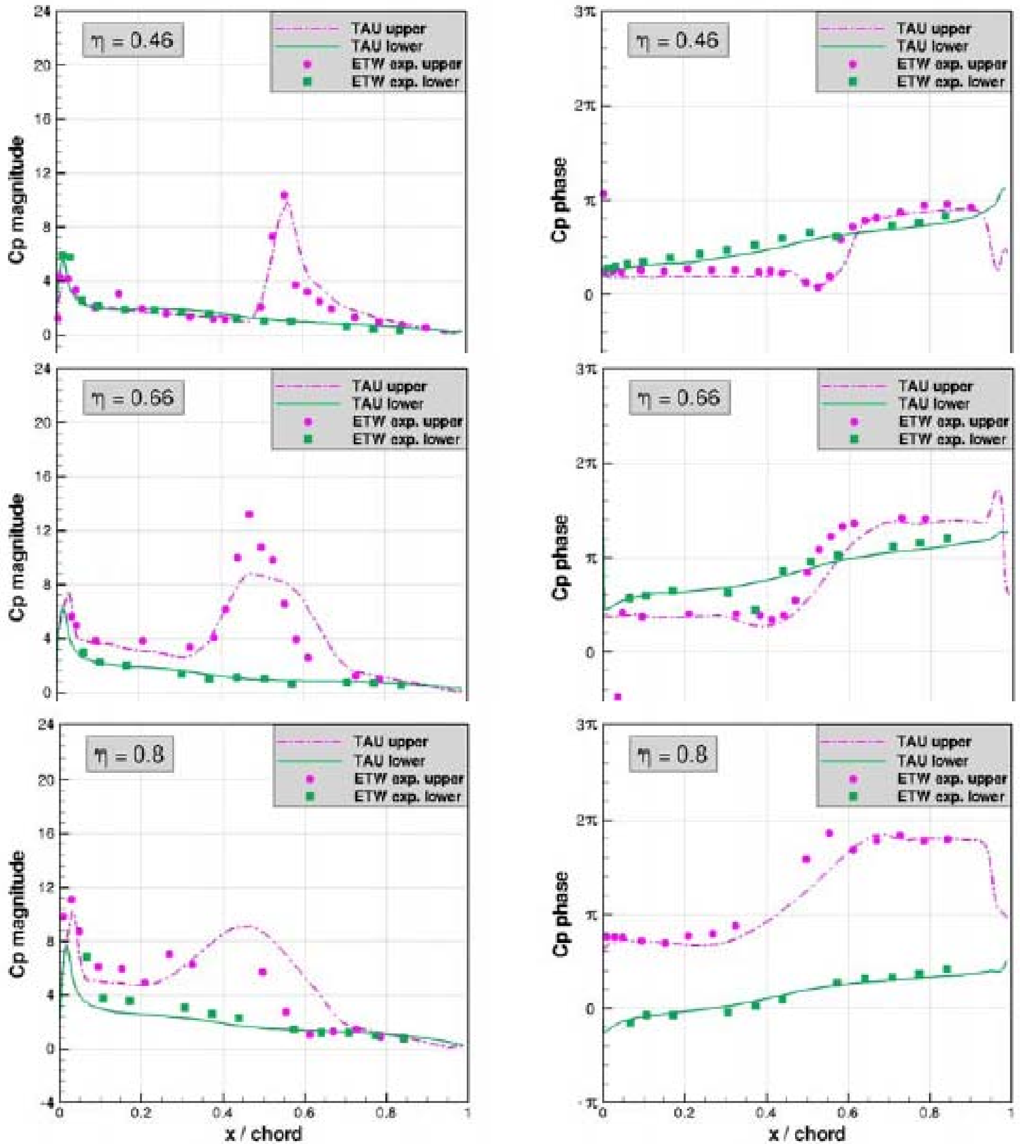
second mode shape, k=0.66, max.

amplitude=3.9e-3 Ma=0.8, Re=7e6,

a

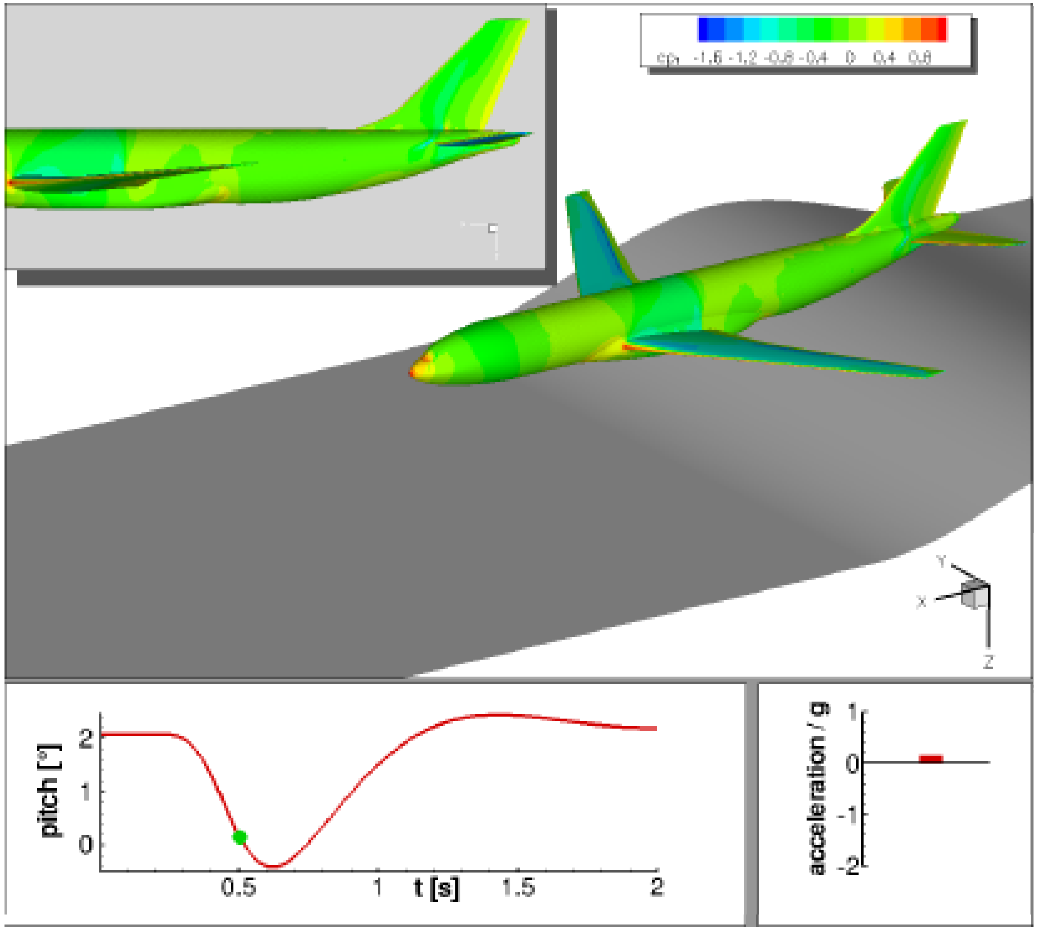






High End Nonlinear Gust Analysis with TAU

- Gust amplitude = 30 m/s, Wavelength = 60 m
- Ma = 0.85, h = 11 km, Re = 72 x 106
- Step 1: Trim steady horizontal flight
- Step 2: Coupling TAU with 6 flight mechanics DOFs
- Enforcement of (1 – cos)-gust velocities at far field and in field
- Source: R,Heinrich, DLR-AS

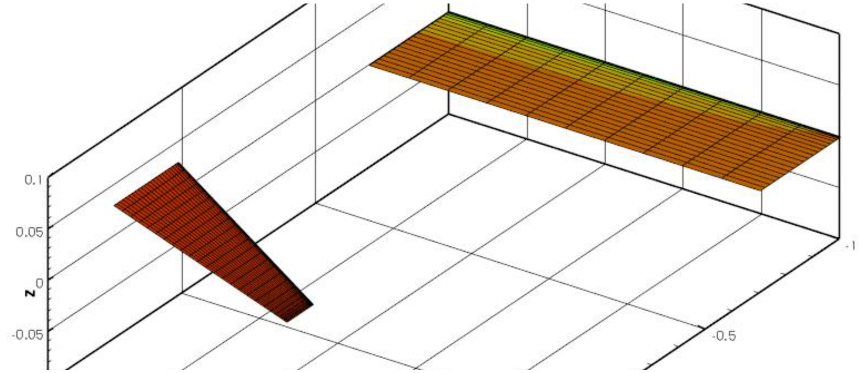


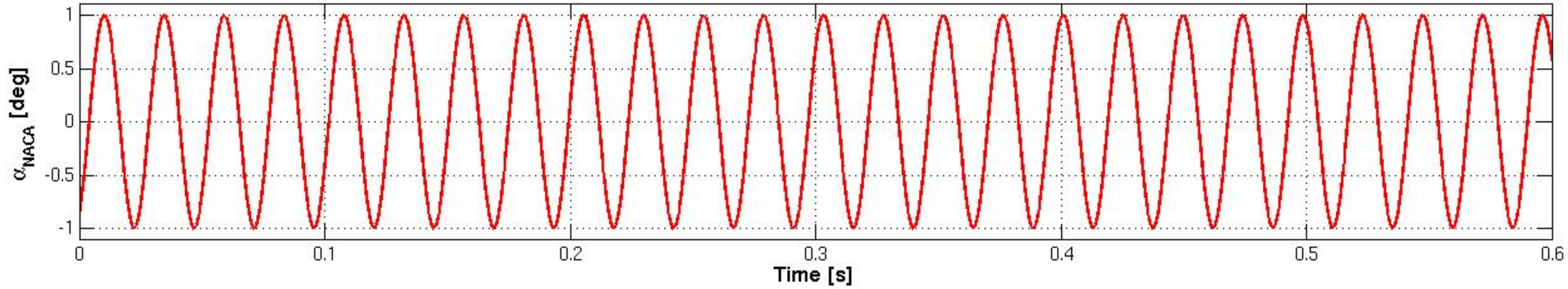
Linear Loads- and Gust Analysis:

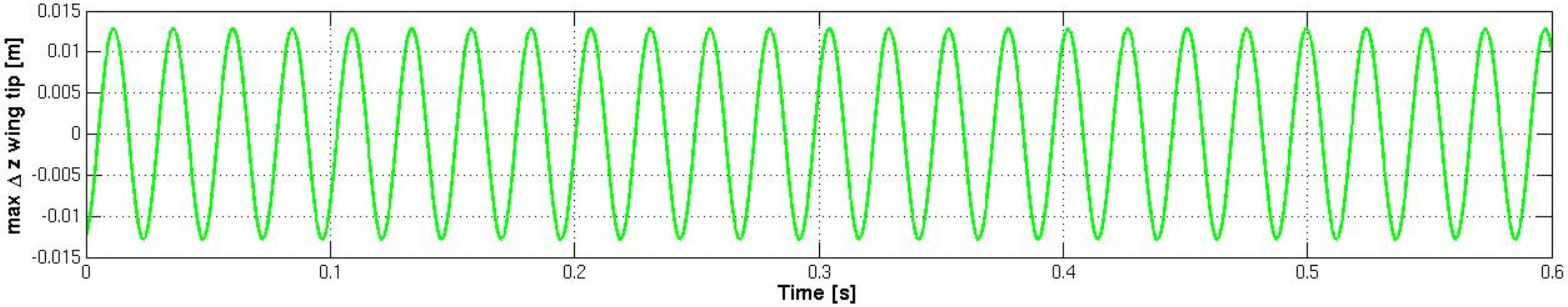
- Ma = 0,75; $\omega^* = 2\pi f\, b / u$ = 0,30914
- Doublet Lattice Aerodynamics

$$\{\Delta c_p\} = [AIC] \cdot \{w_{ind}\}$$

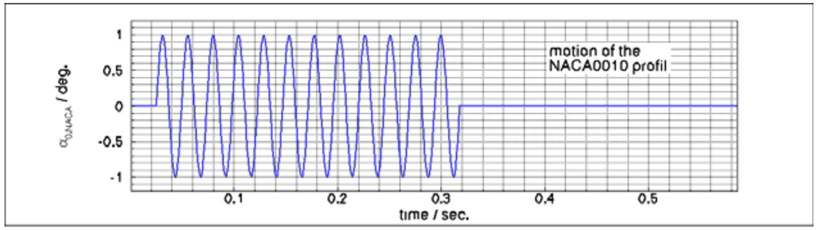
$$w_{ind} = \alpha \cdot (1 + i \cdot x \cdot \omega^* / b)$$

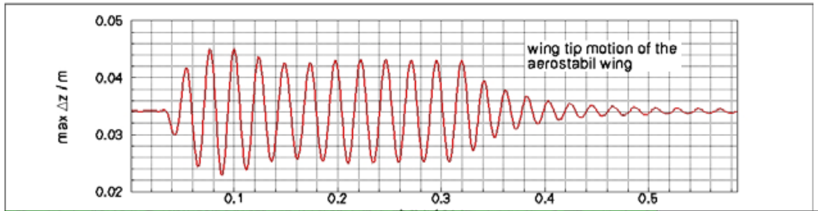


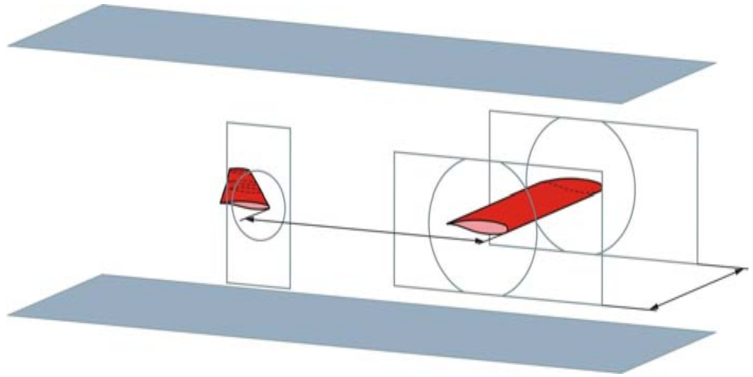


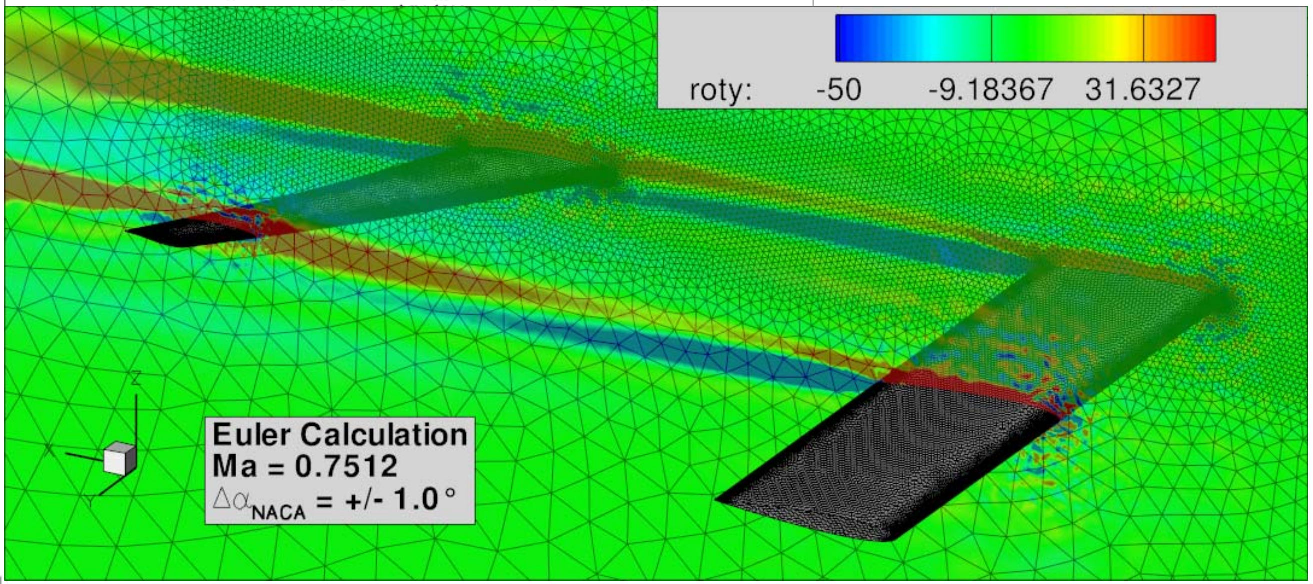


Dynamic Response to Wake
Windtunnel test – generic model for gust response







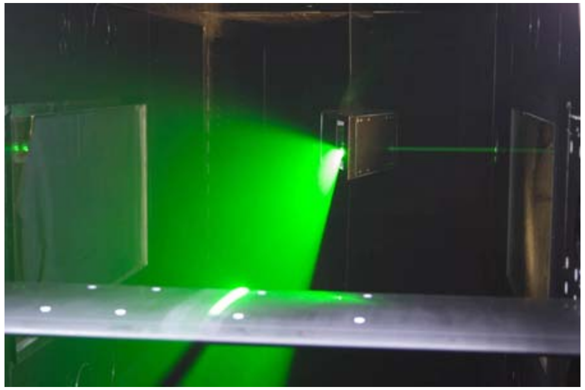


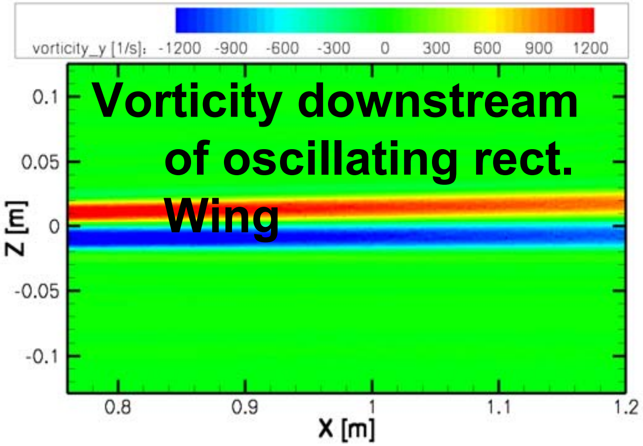
Interference Problems

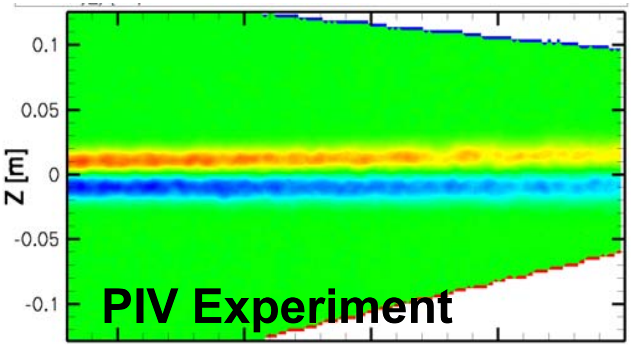
Atmospheric turbulence and gusts,

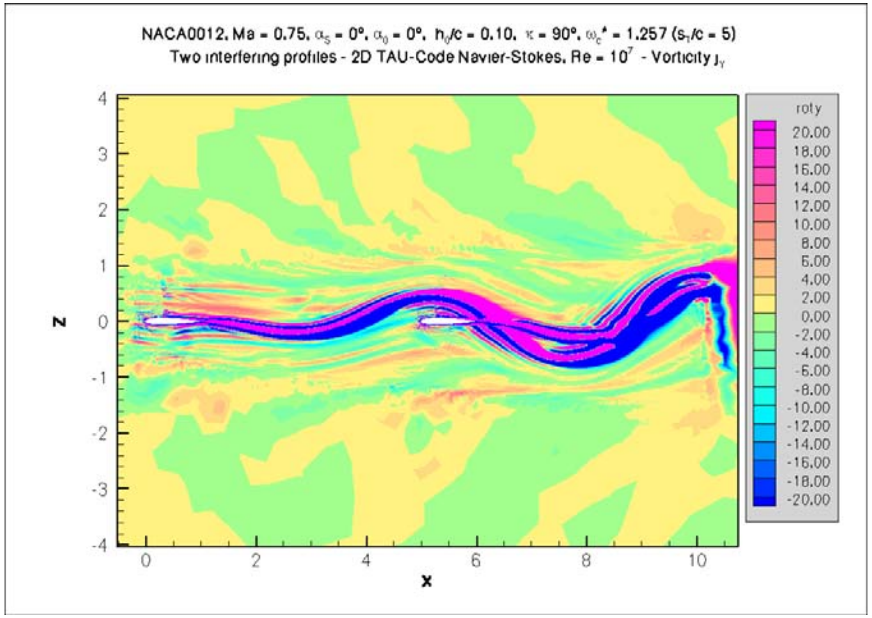
Wake and vortex interference

Numerical Simulations require fine grids for proper wake resolution



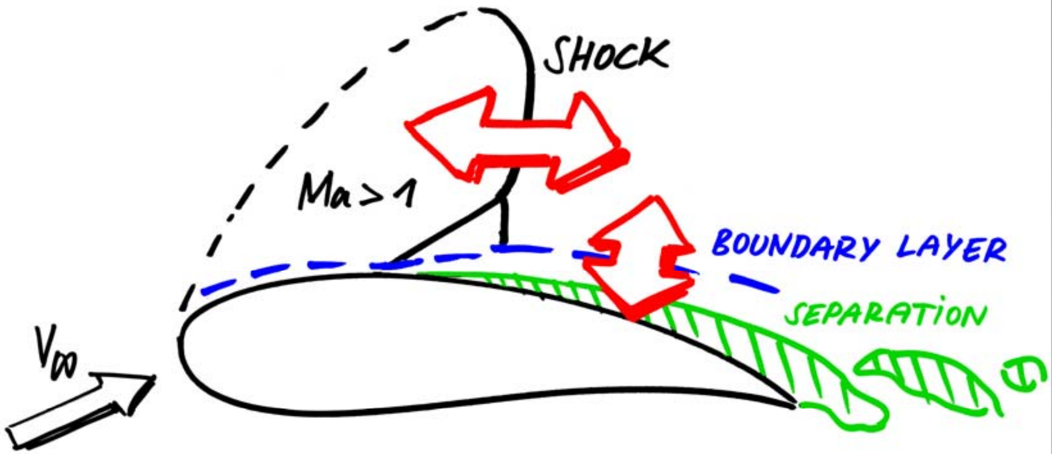


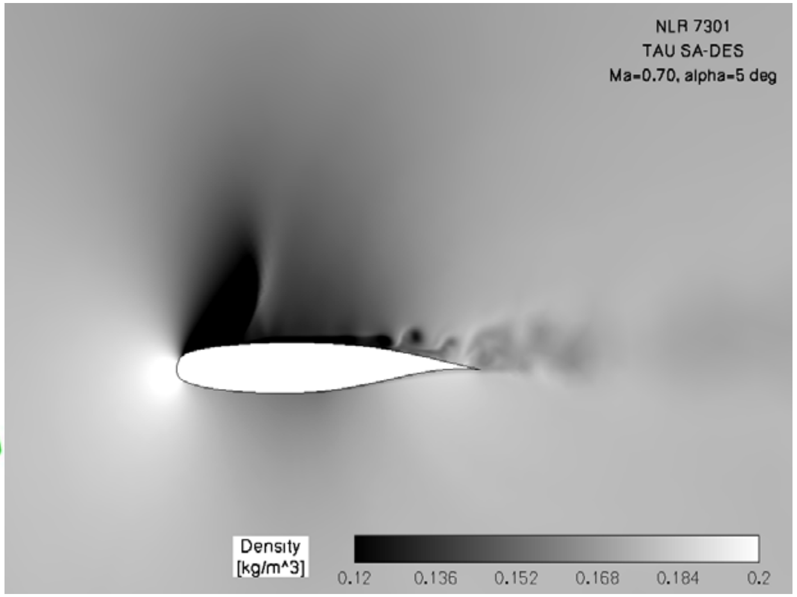




TAU-Simulation: Vorticity for configuration of two oscillating airfoils

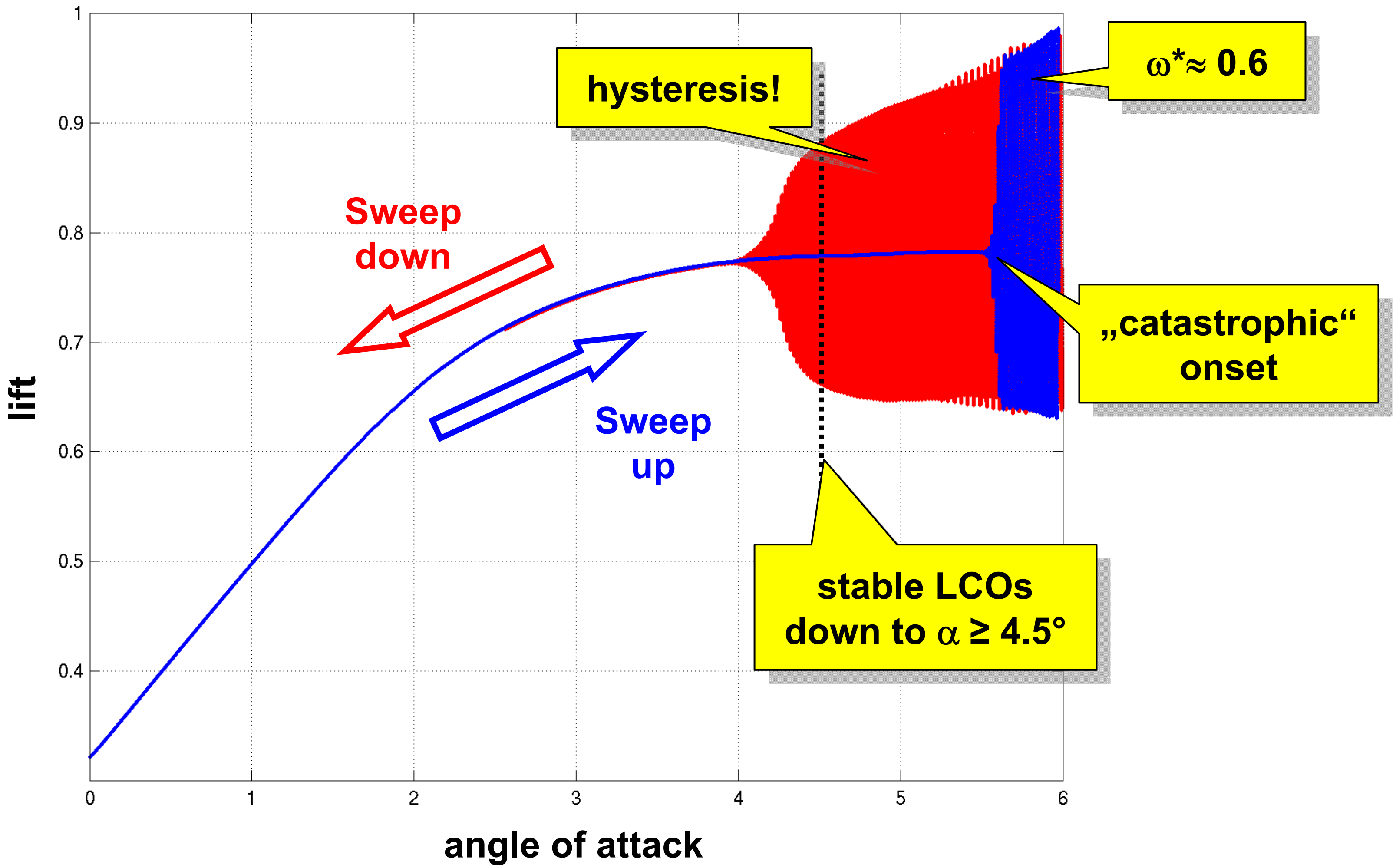
The “shock buffet” phenomenon





- Pure aerodynamic, **self-excited shock oscillations** due to shock-boundary layer interaction in transonic flow
- Large-scale, low-frequency (Sr≈0.1), beyond critical (Ma_∞, α)
- Fixed airfoil, i.e. **no elasticity** here
- Heavy loads, may couple with structural dynamics (“buffeting”)
- Can be simulated with CFD (qualitatively)
- **Physics of feedback mechanism still subject of discussion!**

Shock Buffet - direct simulation



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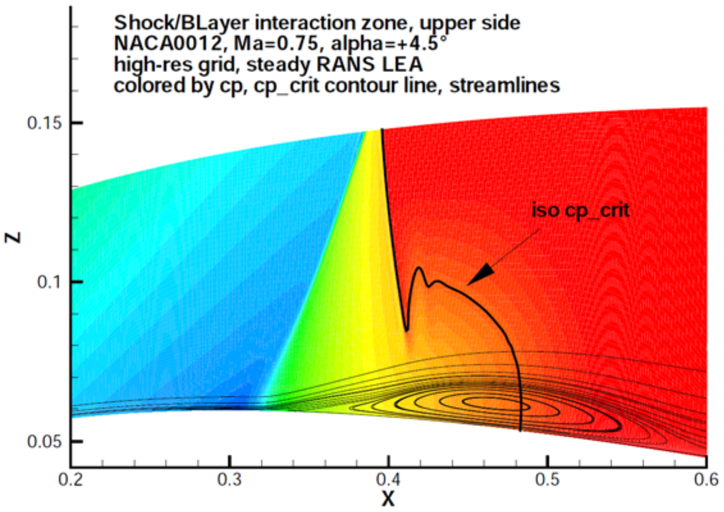
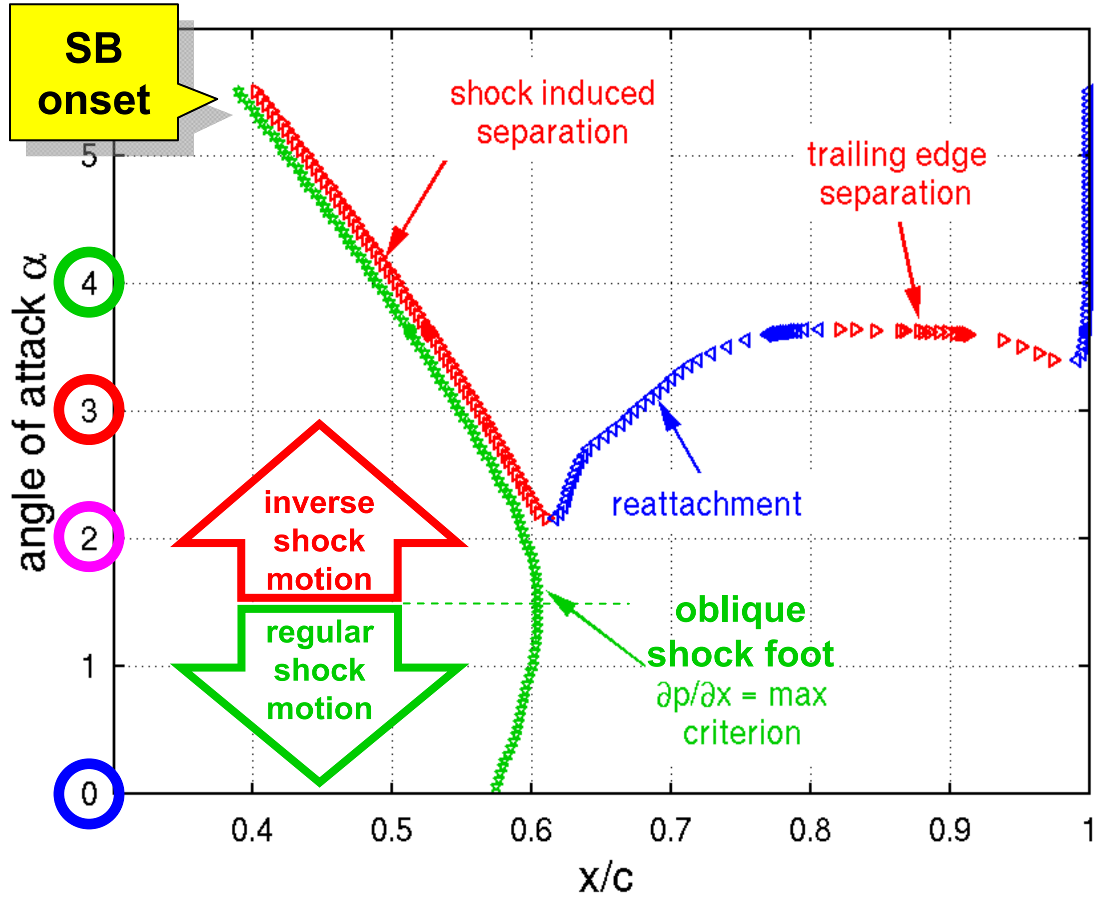
Shock Buffet - Four subcritical mean flow fields

- Four different stable 2-d RANS flow fields around a supercritical airfoil at Ma=0.75 and α_0= **0°**, **2°**, **3°**, **4°** :

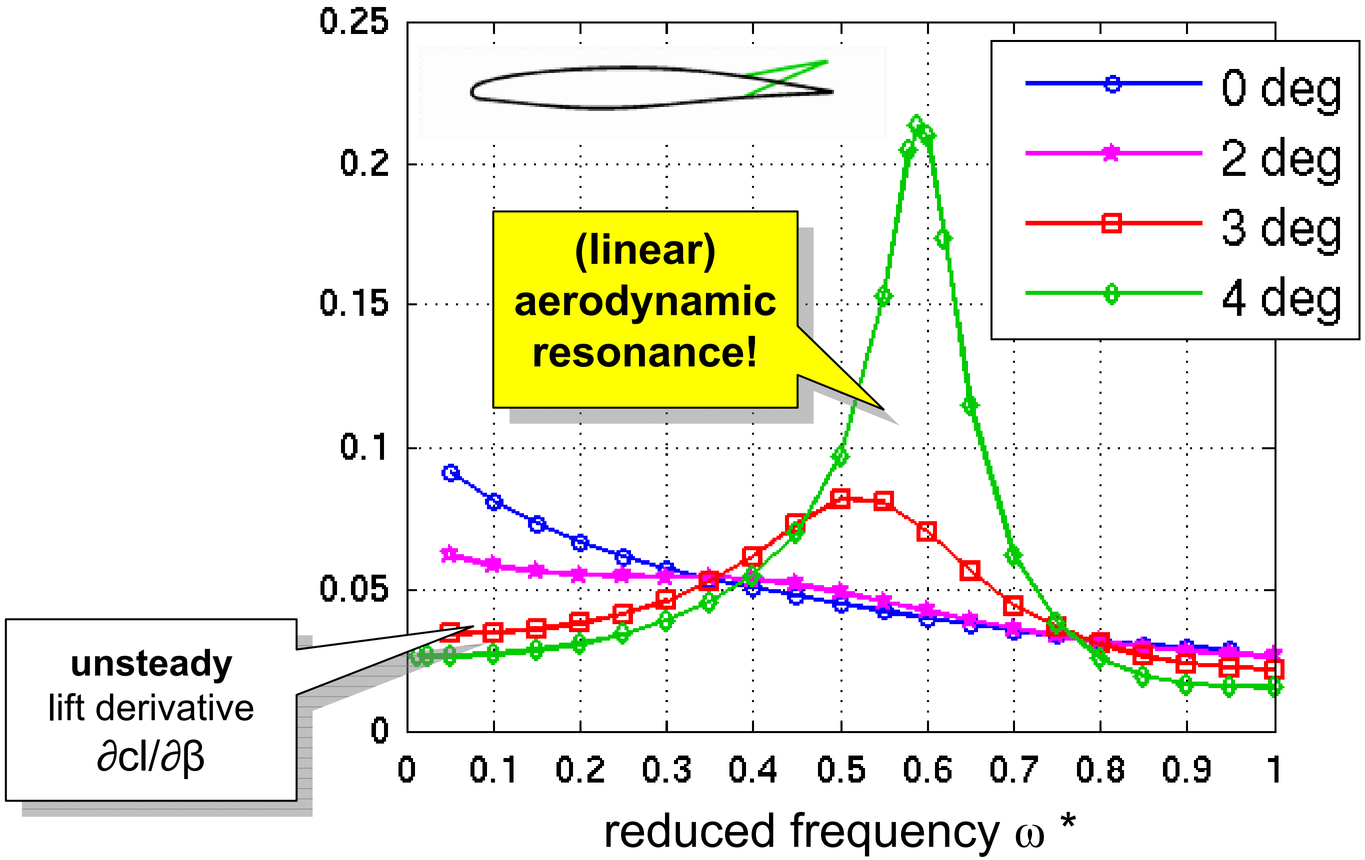




Shock Buffet

Subcritical frequency response

- Excitation of the flow with **(very!) small, harmonic perturbations** in the time domain (arbitrary kinematics)



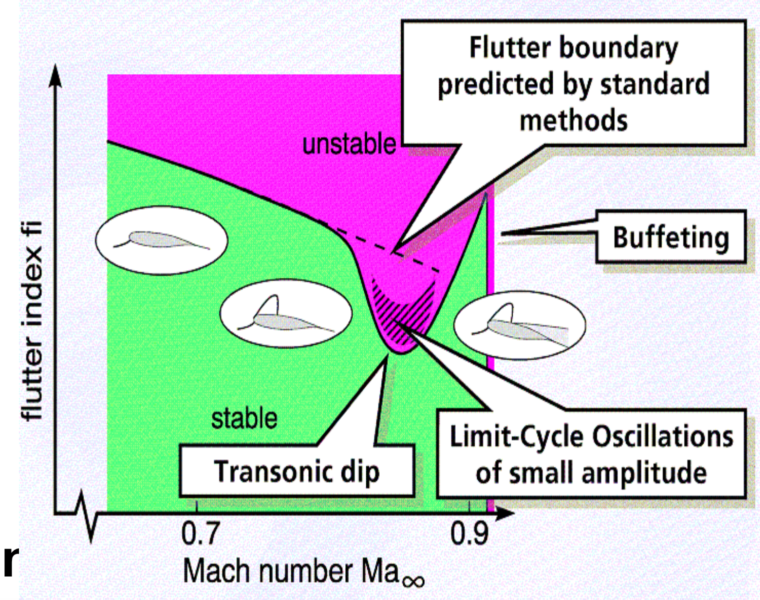
Efficiency Improvement of Flutter Analysis in transonic and separated flow

Flutter analysis of an aircraft needs computations for many parameter combinations:

- Mach numbers: 1-7, Frequencies: 5-12, Symmetric-Antidymmetric: 2, Modes: 40-150,
- Payload/fuel weight: 15-20, trimmed (elasic) flight conddition: 1-3 → <u>> 1 Mio !</u>
- CFD effort for example TAU-URANS, CFD Half model, 5.417 Mio grid cells
- 27 h CPU per single case (32 Prozessors) = 3 Mio Proc.sec!

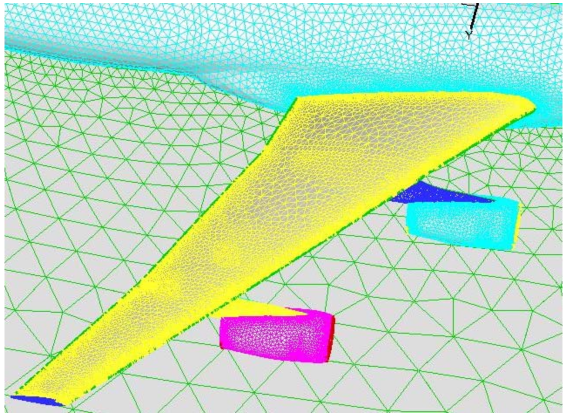
→ Reduktion of CFD effort necessary

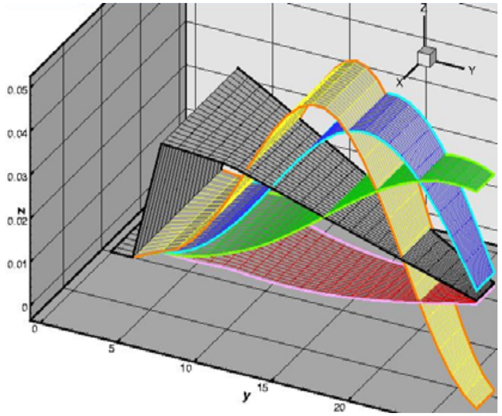
- **Correction of classical subsonic DLM**
- **Transfer Functions**
- **Application of less sophisticated CFD (Euler+boundary-layer)**
- **Linearised CFD**
- **POD (Proper Orthogonal Decompositior**

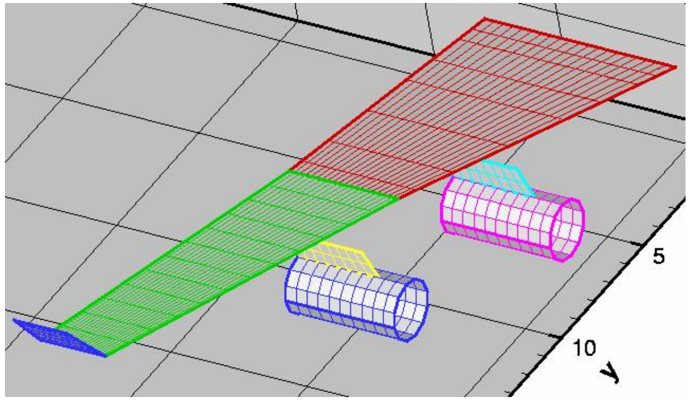


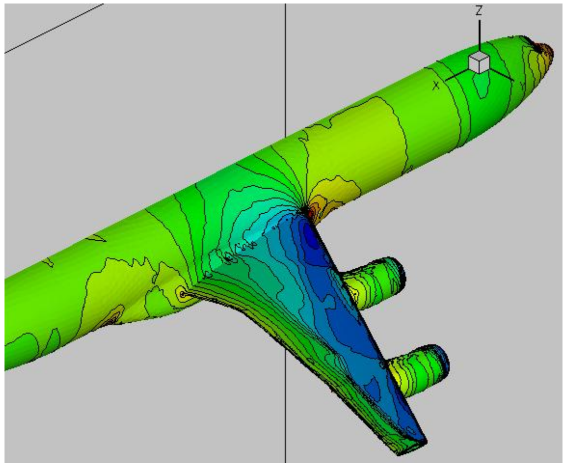
CFD4Flutter – RANS based CFD-Correction of DLM

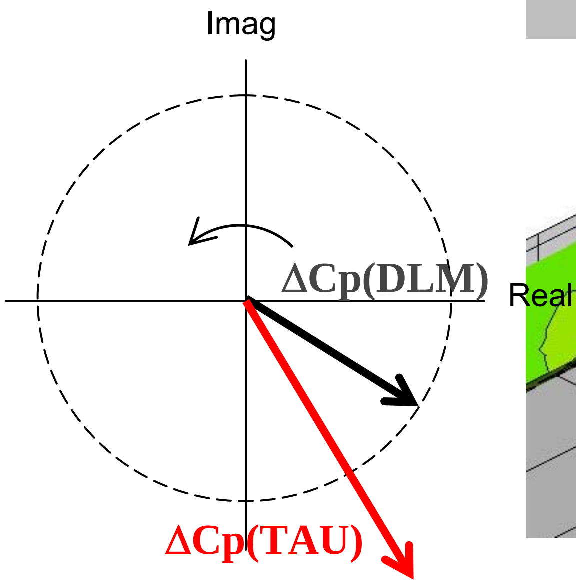
Complete CFD Simulation → for selected Basic modes → correction of DLM Aero

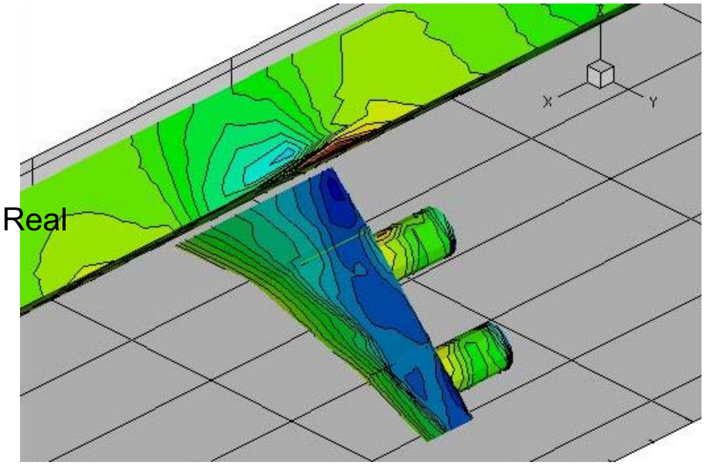








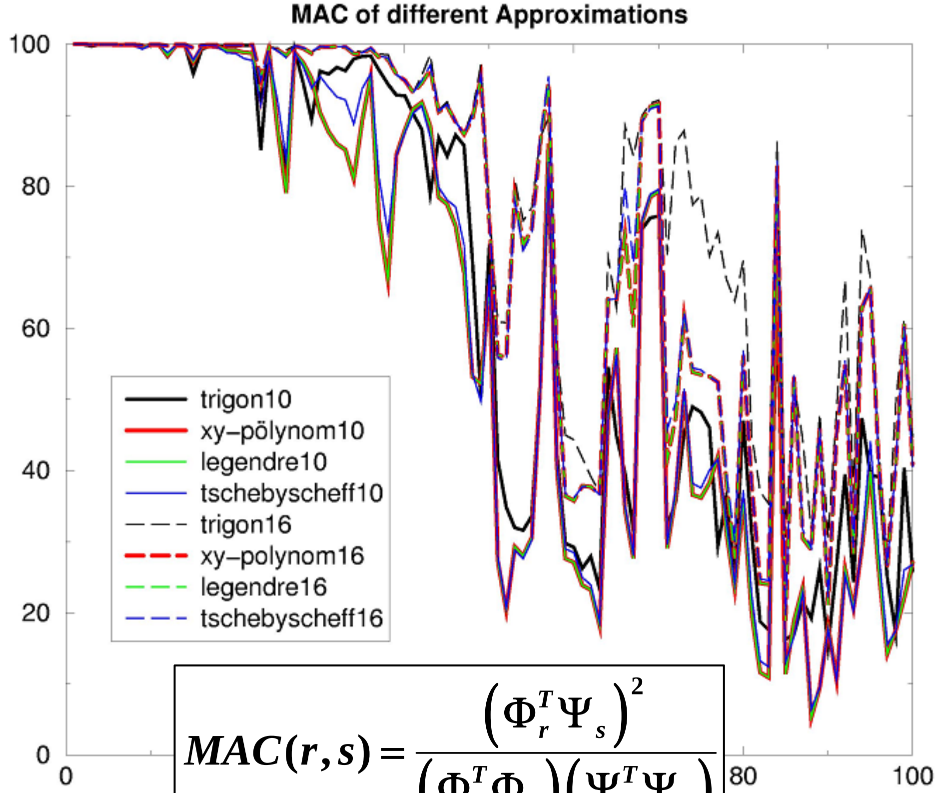




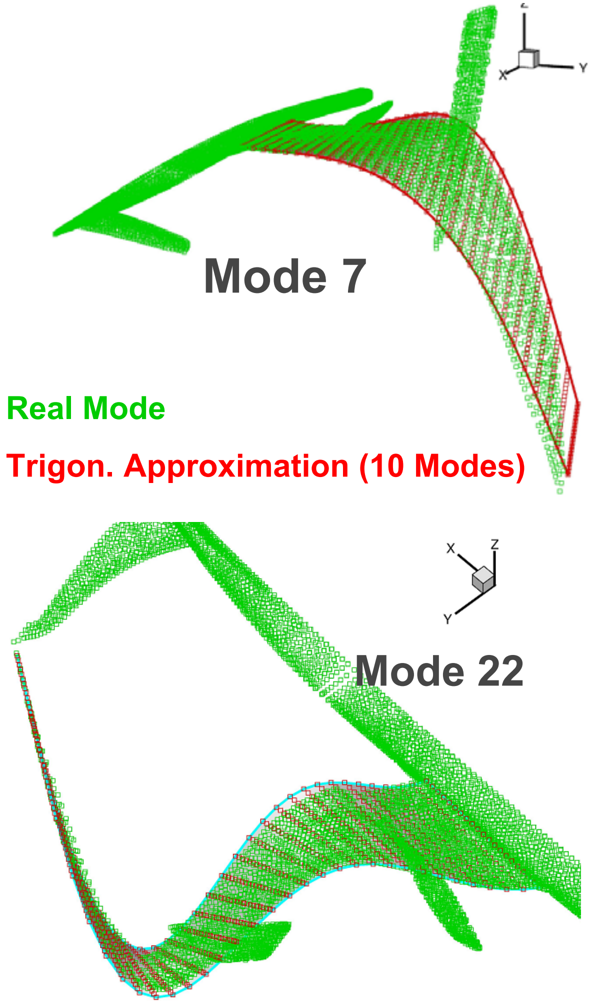
Approximation of Elastic Modes

- 10 synthetic modes sufficient for approximation of first 50 real airctaft modes (MAC values > 80%).
- Trigonometric approach for synthetic modes

First 100 A340–300 Eigen Modes

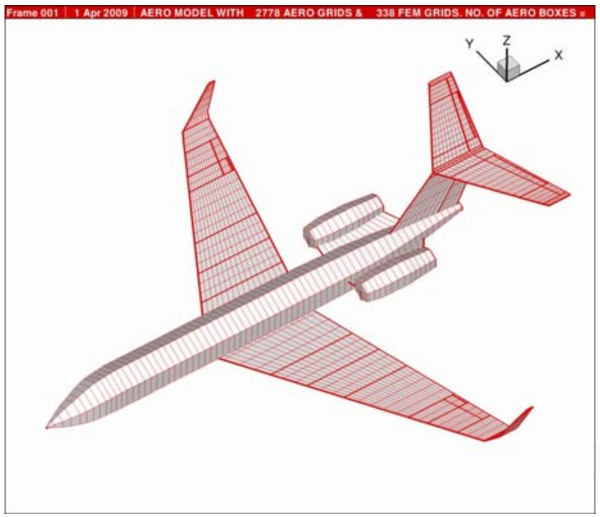


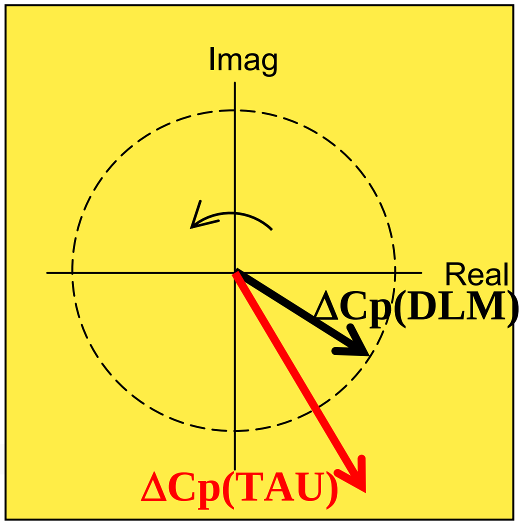
$$MAC(r,s)=\frac{\left(\Phi_r^T\Psi_s\right)^2}{\left(\Phi_r^T\Phi_r\right)\left(\Psi_s^T\Psi_s\right)}$$

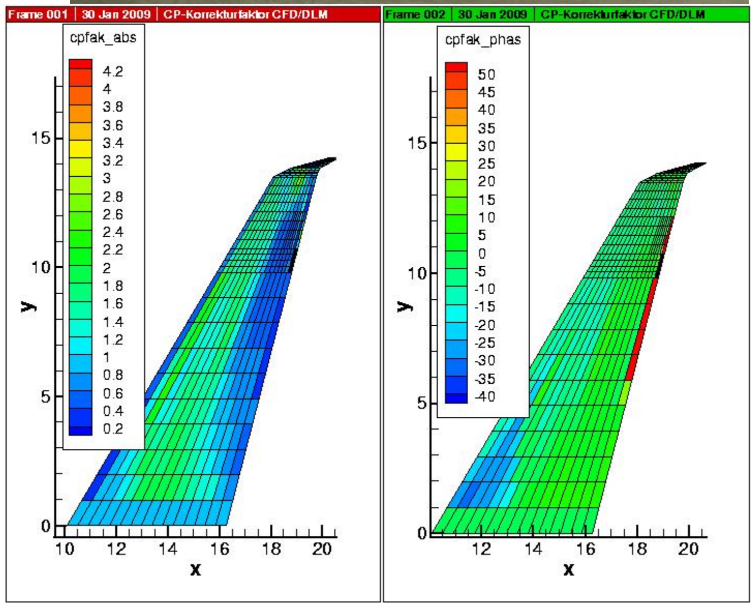


Application to DLR Research Aircraft G550-HALO

- CFD half model, RANS, 5.417 Mio cells,
- Unsteady aero data base for forced oscillations of trimmed aircraft in static aeroelastic equilibrium
- 300 cases (3 Ma, 2 cl, 5 ω^*, 10 synth. modes)
- Flutter computation based on unsteady aerodynamic corrected data, 95 modes from Ground Vibration Test







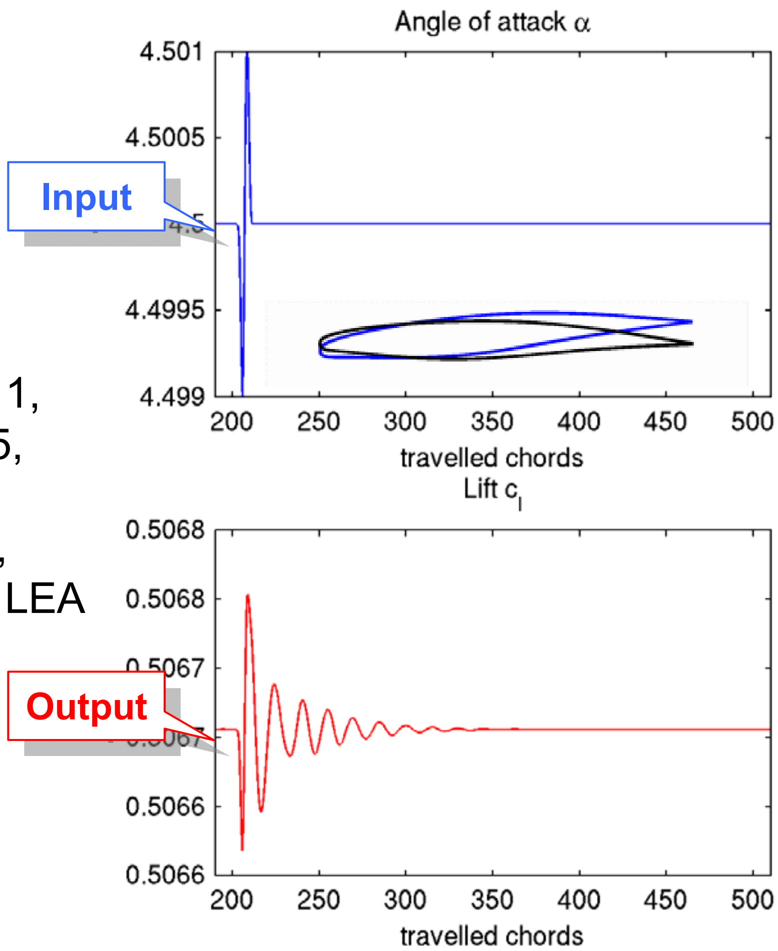
Correction factor (magnitude and phase)
(1. Torsion, Ma=0.8, k=0.25)

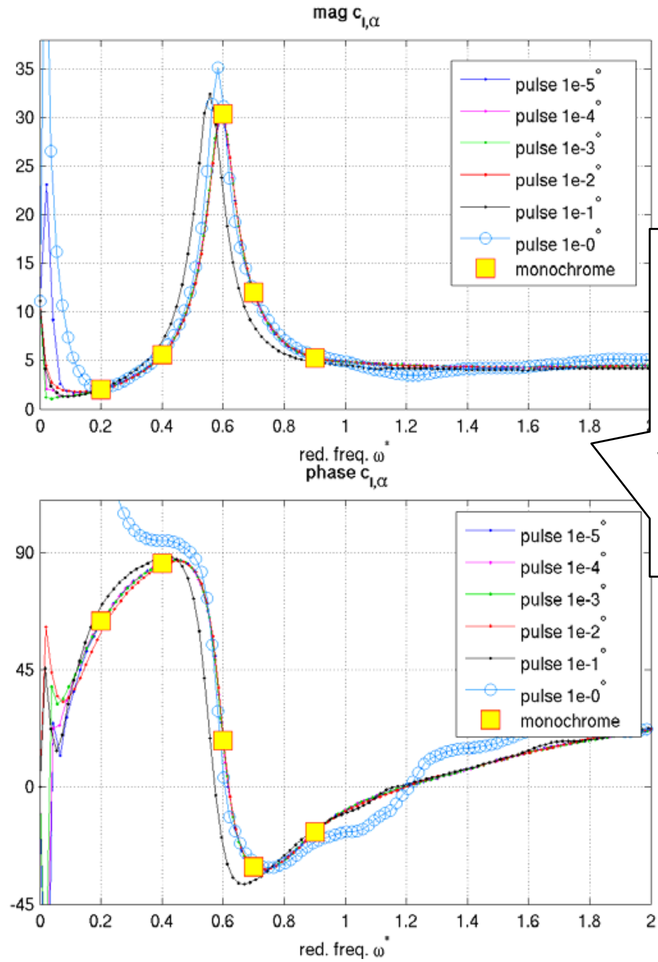
Transfer Functions – Impulse Method

Unsteady 1. Harmonic of lift extracted from pulse excitation of airfoil.

<u>Linearity</u> of transonic and separated flow for small disturbances!

BAC 3-11,
Ma=0.75,
α_0=4.5°,
TAU 2D,
URANS LEA

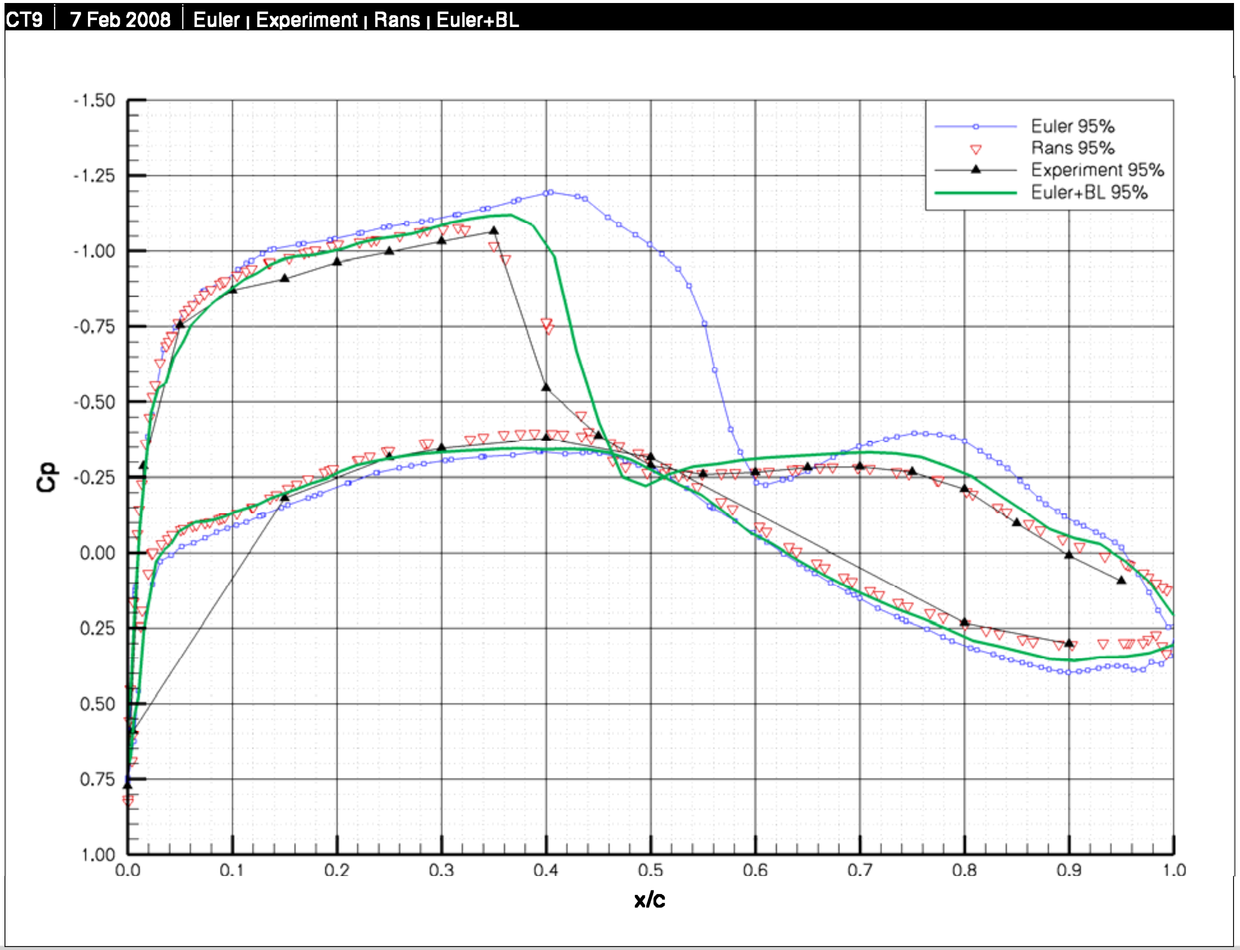




frequency-domain Magnitude of output Scaled with magnitude of input

Euler – Boundary layer Coupling
Testcase LANN CT9 with shock-induced flow separation

- TAU with 2D inverse Integral Boundary Layer Method
- Carter Coupling
- For attached flow o.k.
- Not for separated flow



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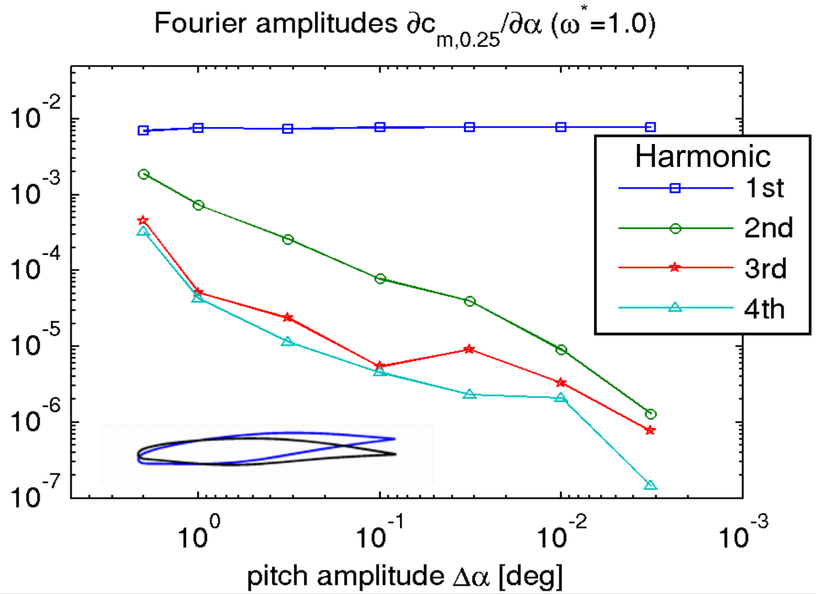
Linearised CFD

Justification

- Small perturbations of boundaries → small linear perturbations of (nonlinear) mean flow field
- Mean flow may comprise shock waves and flow separation
- Motion of shock waves or separation bubbles are nearly proportional to boundary perturbation
- This apprroximation is sufficient for aerolestic stability analysis

Difficulties and limits

- LCO (large shock motion or separation motion)
- Linearisation for separated flow difficult
  Linearisation of turbulence models?
- Linearisation of transition?



Linearised Frequency Domain Solver (LFD)

- Unsteady RANS Equation (1): $$\frac{du}{dt} + R(u, x, \dot{x}) = 0$$
- Fourier series expansion
- of u(t) and x(t)

$$u(t) = \bar{u} + \tilde{u}(t) = \bar{u} + \sum_k \left(\hat{u}_k e^{ik\omega t}\right)$$

$$x(t) = \bar{x} + \tilde{x}(t) = \bar{x} + \sum_k \left(\hat{x}_k e^{ik\omega t}\right)$$

- analysis of small periodic motions
- **Liniearisation** of (1)
- about steady equilibrium condition:

$$\frac{du}{dt} + \left.\frac{\partial R}{\partial u}\right|_{\bar{u},\bar{x}} \tilde{u} + \left.\frac{\partial R}{\partial x}\right|_{\bar{u},\bar{x}} \tilde{x} + \left.\frac{\partial R}{\partial \dot{x}}\right|_{\bar{u},\bar{x}} \dot{\tilde{x}} = 0$$

- Fourier expansion yields a complex valued linear system of equations

$$Ax = b$$

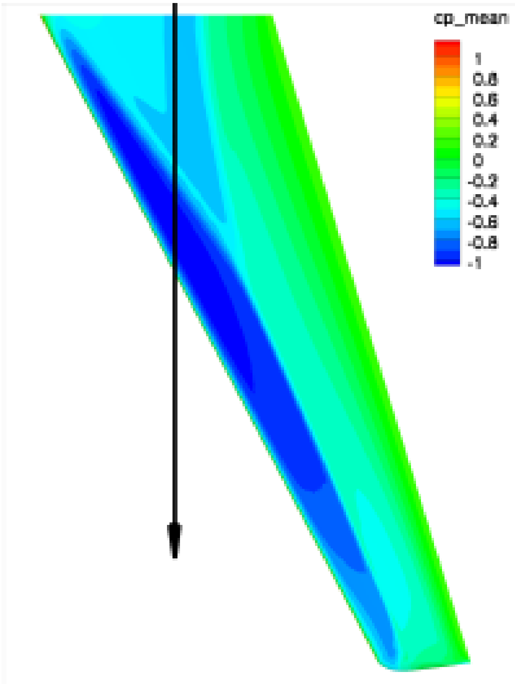
$$A = \begin{pmatrix} \frac{\partial R}{\partial u} & -k\omega I \\ k\omega I & \frac{\partial R}{\partial u} \end{pmatrix} \quad x = \begin{pmatrix} \hat{u}_{real} \\ \hat{u}_{imag} \end{pmatrix} \quad b = \begin{pmatrix} \frac{\partial R}{\partial x}\hat{x}_{real} + k\omega \frac{\partial R}{\partial \dot{x}}\hat{x}_{imag} \\ -\frac{\partial R}{\partial \dot{x}}\hat{x}_{imag} - k\omega \frac{\partial R}{\partial x}\hat{x}_{real} \end{pmatrix}$$

- b computed by: $$\frac{\partial R}{\partial x}\hat{x}_{real} = \frac{\Delta R(\bar{u}, \bar{x} \pm \epsilon\hat{x}, 0)}{2\epsilon} \qquad \frac{\partial R}{\partial \dot{x}}\hat{x}_{imag} = \frac{\Delta R(\bar{u}, \bar{x}, \pm\epsilon\hat{x})}{2\epsilon}$$

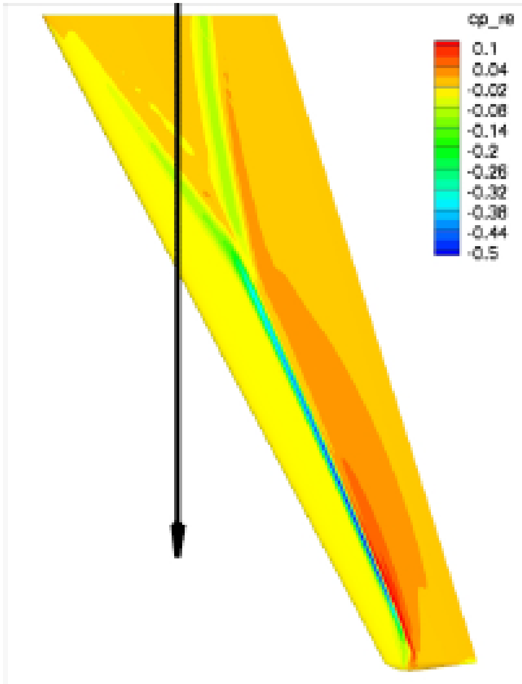
LFD – RANS TAU Validation

LANN wing CT5, Ma=0.82, Re=7.5 mio, α=0.6°, $\Delta\alpha$=0.25°, ω^*= 0.204, pitch

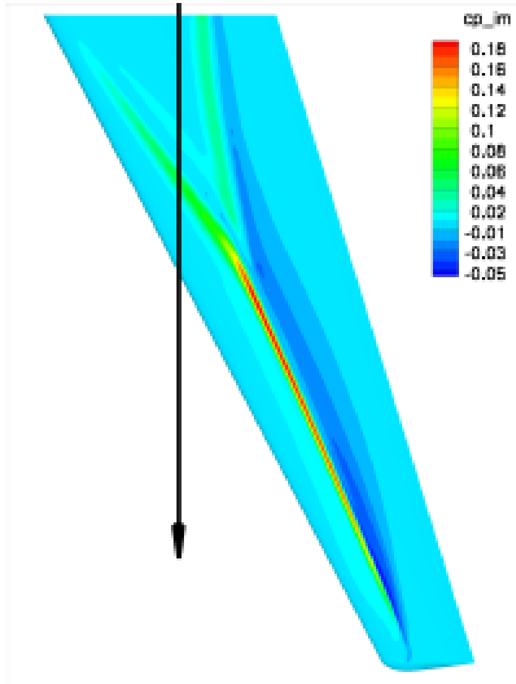
Cp contour on upper surface of LANN wing CT5



(a) C_p^{mean}

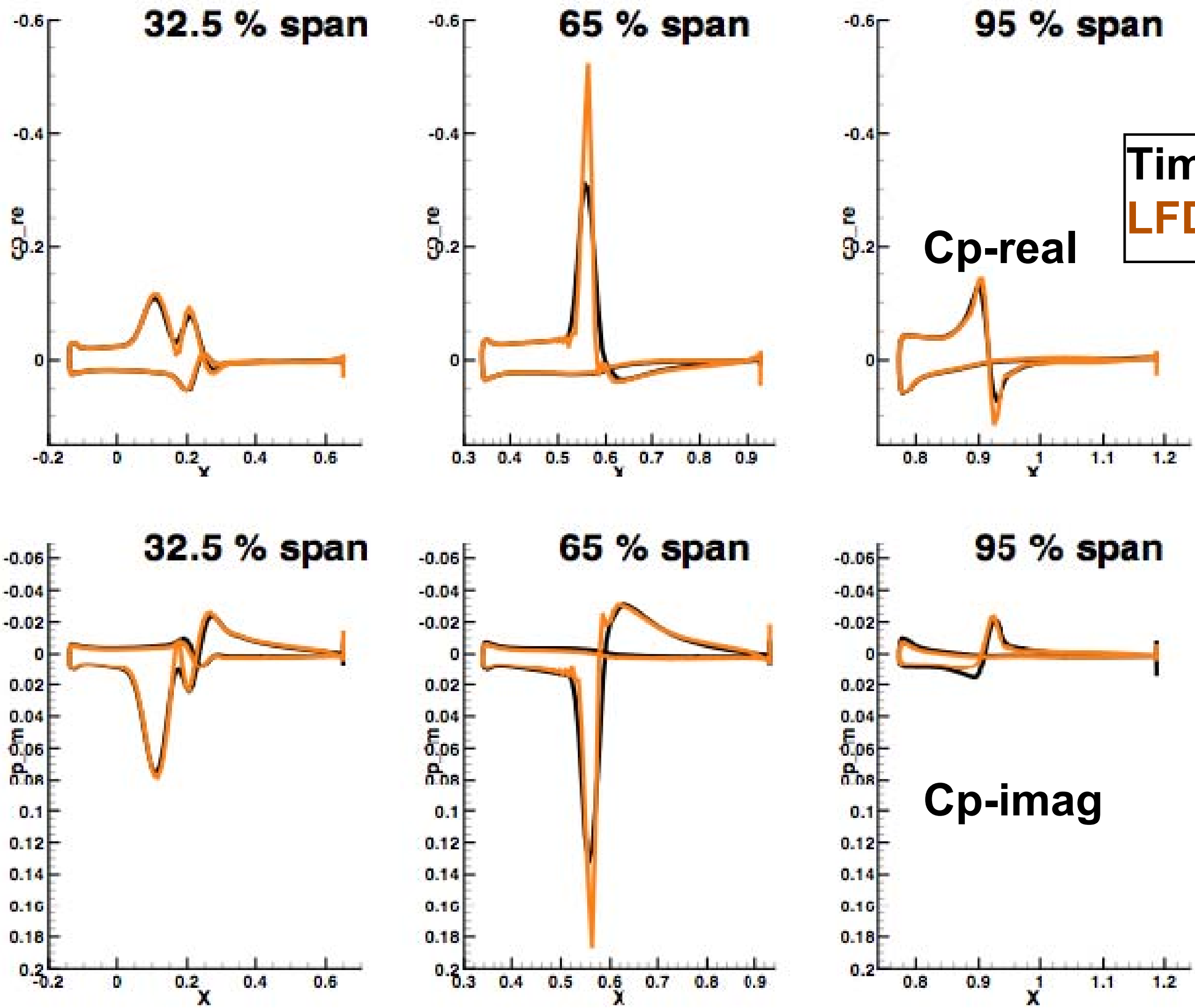


(b) C_p^{real}



(c) C_p^{imag}

LFD – RANS TAU Validation First Harmonic of Cp: LANN wing CT5



Time domain nonlinear
LFD

POD – Proper Orthogonal Decomposition

Objective: Generate an optimal basis of small order for a manifold of required CFD results.

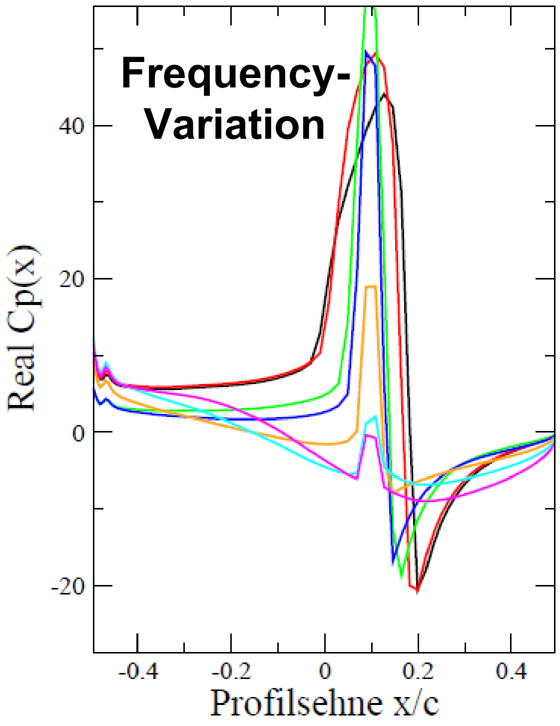
Computation of solutions **(snapshots)** for:

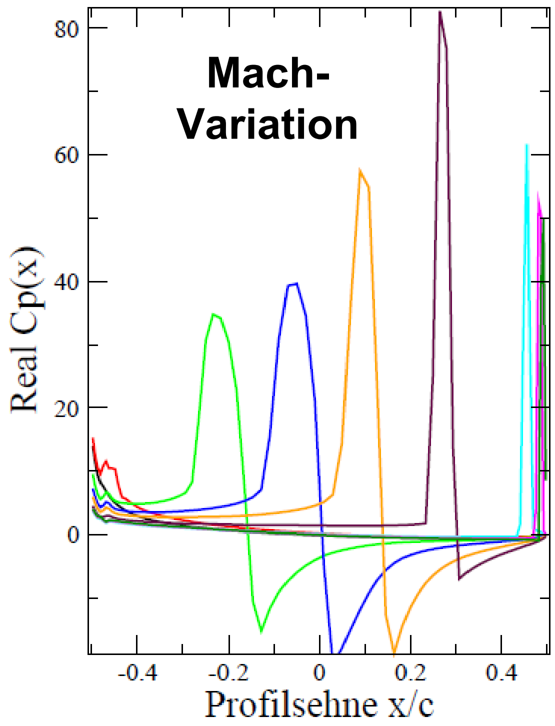
- 1. harmonic of unsteady flow fields
- 1. harmonic of surface Cp distribution
- Several parameter combinations (flow solutions for varying frequency, oscillation mode, Mach number, AoA, …, → **N snapshots**

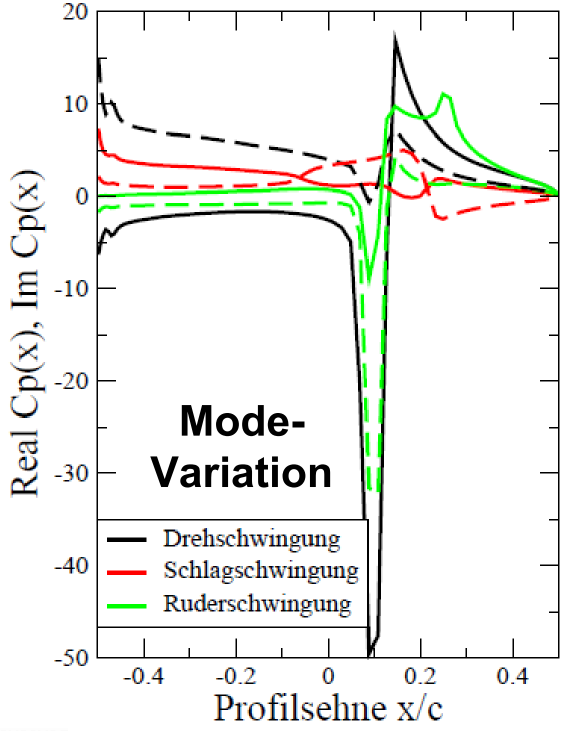
- Fill these solution vectors in colums of a matrix → Snapshot-Matrix S
- Compute Eigenvalues and Eigenvectors of the symmetric $W=S^TS$
- Take those p Eigenvectors V, whose Eigenvalues have the biggest magnitude → p vectors V
- → POD-Basis $\Phi = SV$
- The N snapshot solutions and even more can be approximatad by superposition of p POD basis vectors: $S_i = \Phi\, w_i$

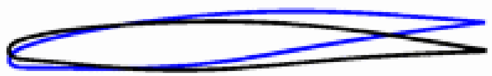
POD – Example: Snapshots of 2D Oscillating Airfoil

- **Unsteady surface pressure Cp-distribution (Real- und Imag.)**
- **NLR7301-airfoil, variation of: Ma, α, ω*, oscill. Modes (9 , 7 , 5 , 3)**
- **945 simulations (Snapshots)**

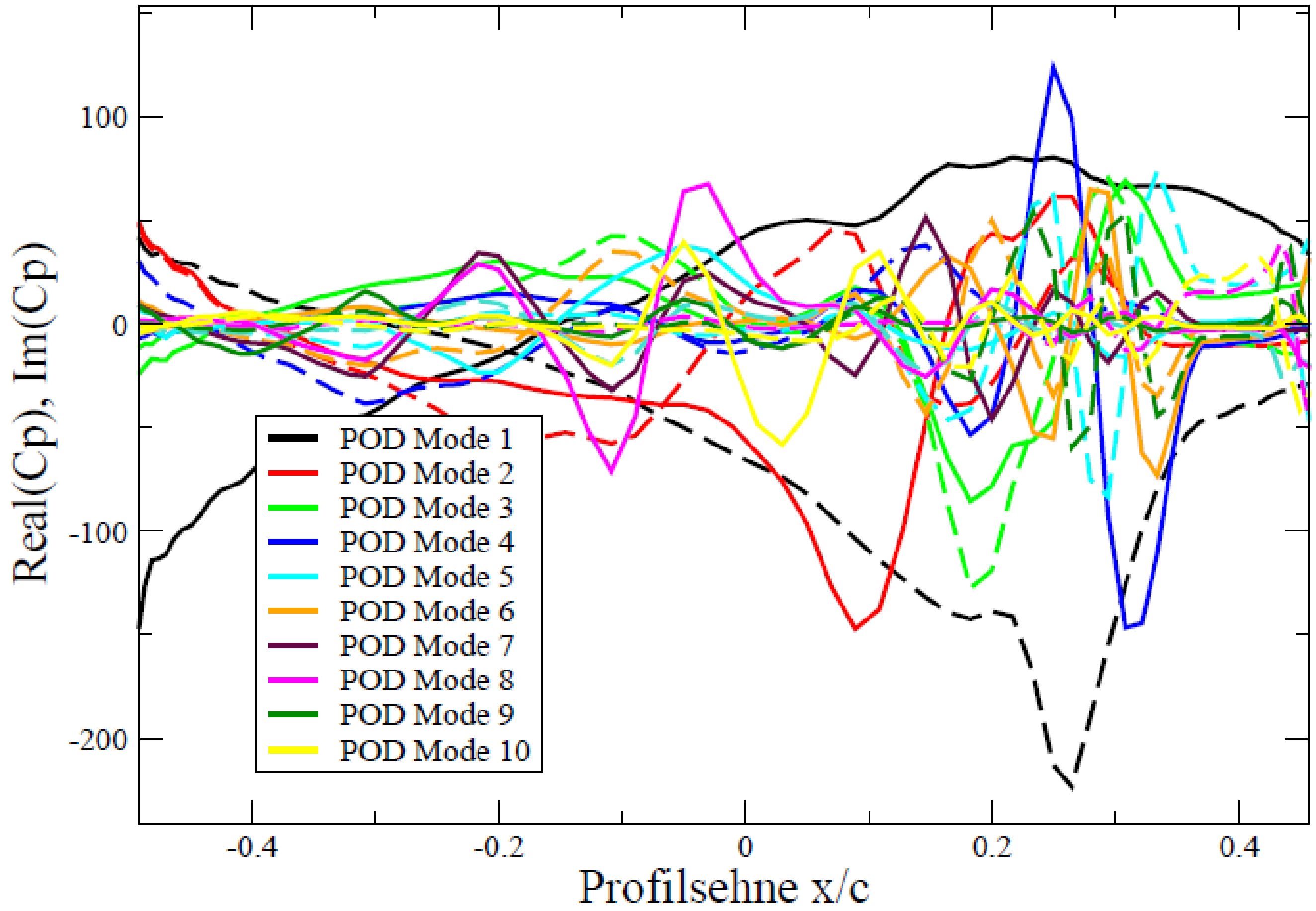






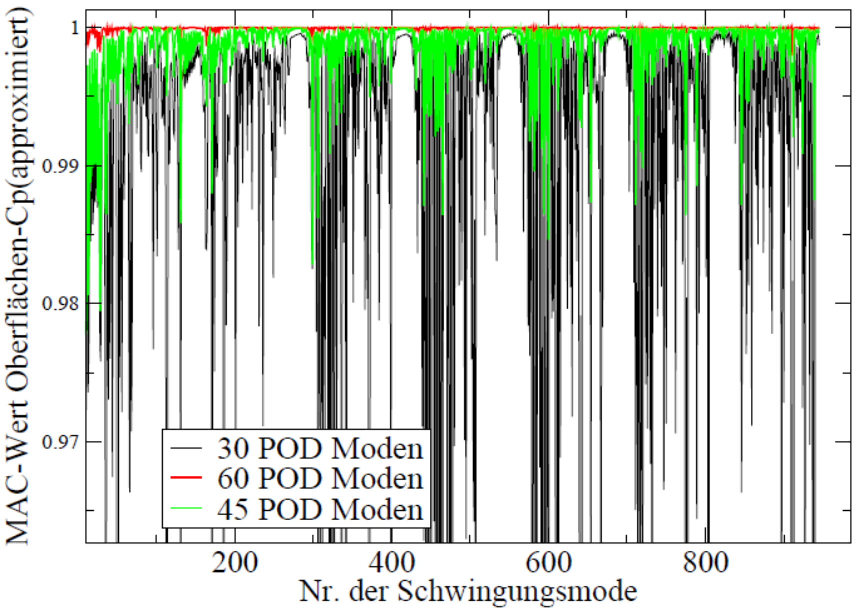


The first 10 POD Modes seem to have no physical meaning

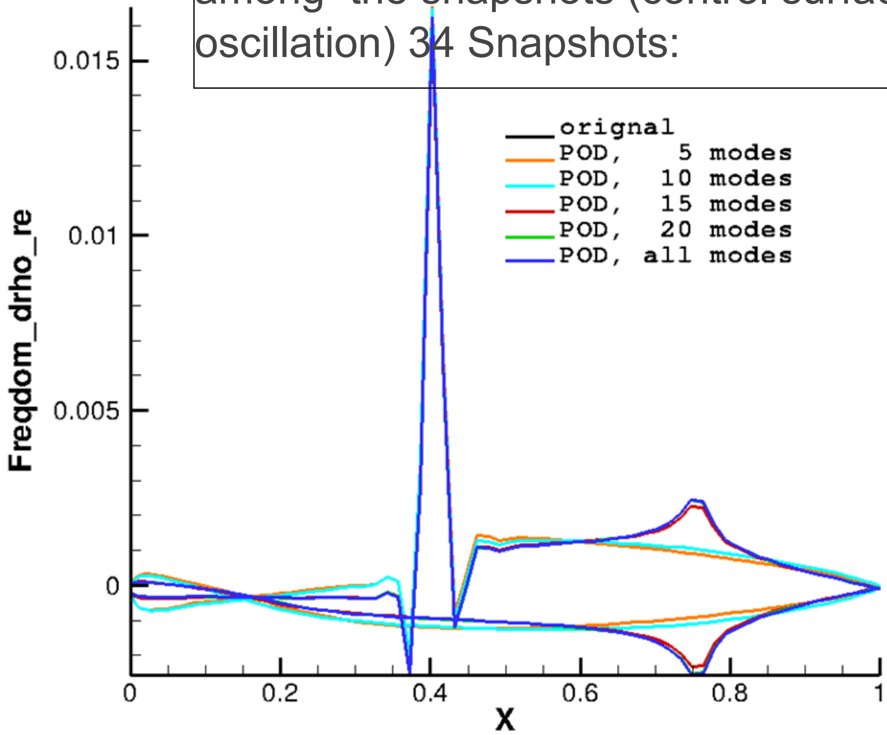


POD

- A reduced POD Basis of vectors Cp(x) can be derived, all snapshots can be reconstructed by linear superposition.
- Only 45 POD POD modes sufficient to construct all 945 Snapshots → reduction of computational effort by factor of 20 ?
- But: POD modes without physical meaning
- Problem: proper choice of snapshots



Other example: case, which was not among the snapshots (control surface oscillation) 34 Snapshots:



Conclusion

- Unsteady CFD methods (RANS) are well validated by windtunnel tests
- for aeroelastic applications CPU effort has to be reduced significantly
- Different methods are developed and tested
- A combination of several methods is promising (factor 1000)