Numerical Aeroelastic Simulation of Aircraft

Holger Hennings, DLR – Inst. of Aeroelasticity

MUSAF II COLLOQUIUM - AROUND AIRCRAFT & WITHIN ENGINES
18-20 SEPTEMBER 2013, TOULOUSE, FRANCE

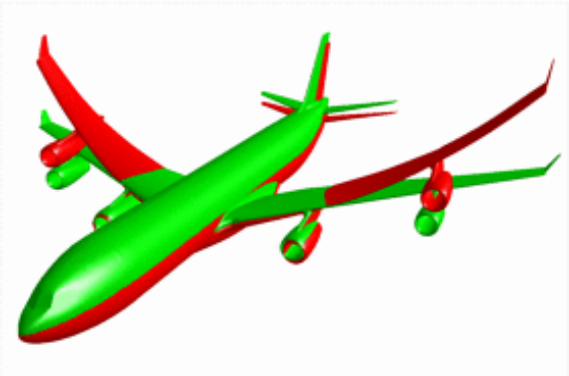
DLR

Aeroelasticity

(relevant to fixed-wing aircraft)

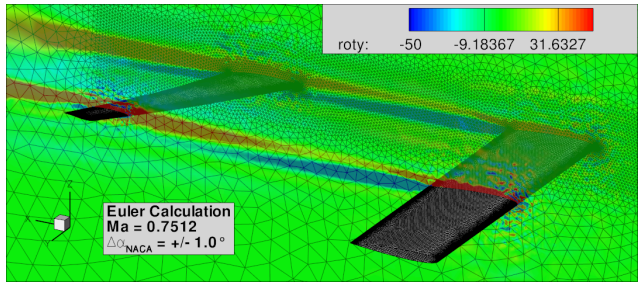
Flutter stability

Limit cycle oscillations



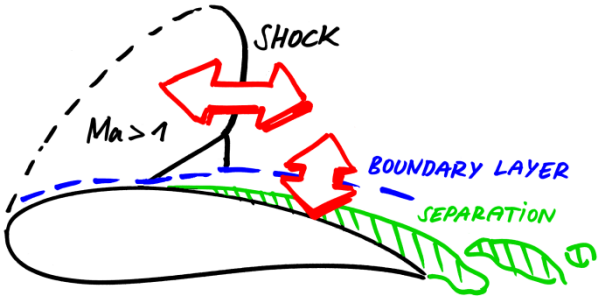
Forced Response

Gust response
Wake vortex
Tail buffeting



Vibration due to flow instabilities

Seperated flow
Bluff bodies
Shock buffet



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Vibration due to flow instabilities

1. Linear Frequency Domain Solver
2. Laminar Flow, Flutter Speed
3. Shock Buffet
4. Flutter Analysis

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Linear Frequency Domain (LFD) Solver

Thormann / Widhalm
IFASD 2013

Motivation LFD

Flutter, Gust Response

- analysed in frequency domain
- many parameter combinations have to be simulated

Accuracy of RANS required

RANS expensive

LFD could save time

Validation LFD

Assuming small amplitudes of motion

RANS equations can be linearized

Transformed into frequency domain

Validation of LFD:

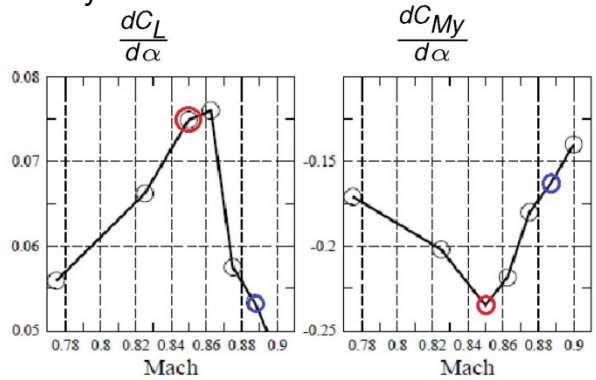
LFD solution and RANS time domain solution

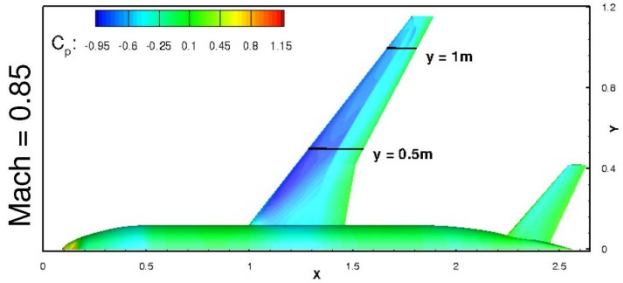
should be the same for small amplitudes

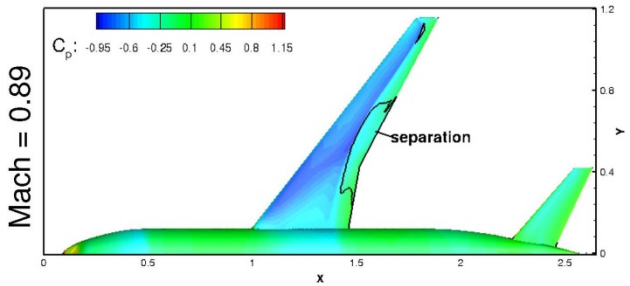
Validation case

- Fermat-Model
- $4 \cdot 10^6$ grid points
- $Re = 5 \cdot 10^6$
- Spalart-Allmaras turbulence model
- Rigidly trimned to $C_L = 0.5$
- 2 Mach numbers considered:
  - 0.85 and 0.89

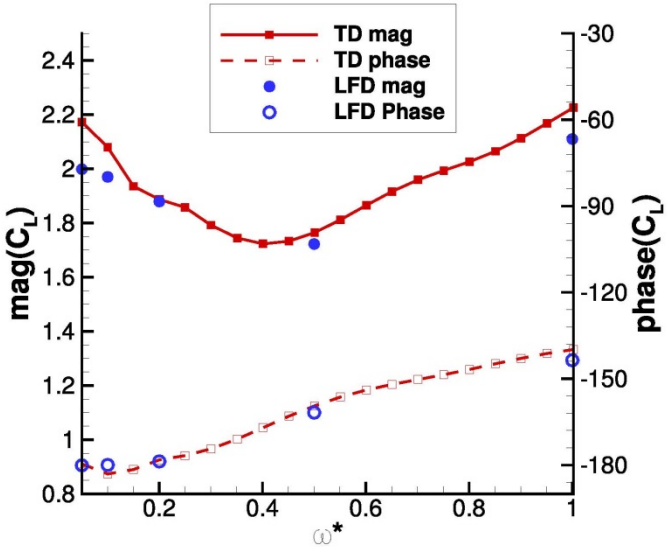
steady flow characteristics



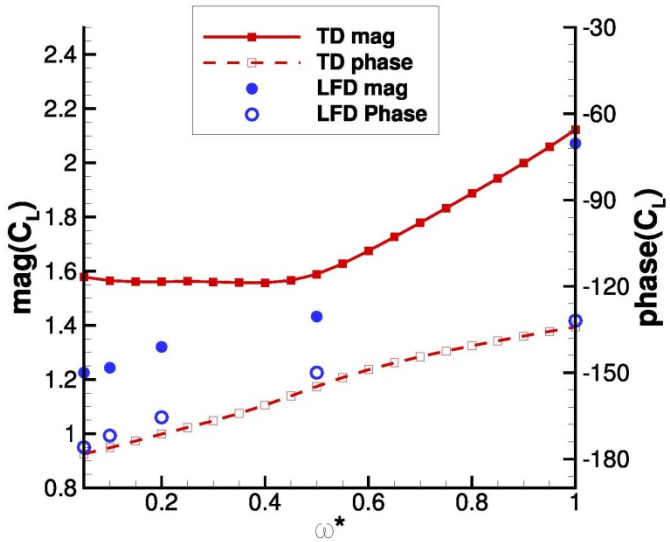




Unsteady results: Transfer function of C_L



Mach = 0.85



Mach = 0.89

- Good agreement between LFD and time-domain results for the attached case
- Differences for the detached case
- LFD and time-domain solver should agree!

Computational Effort

Time Saving Factors:

Case	TD (h)	LFD (h)	ζCPU
Ma = 0.85, 2.85 periods	33.4	0.38	88
Ma = 0.89, 3.09 periods	40.4	0.55	73

Memory requirement:

solver	memory (GB)	M / M_{steady}
steady RANS	7.20	1.00
time domain RANS	7.58	1.05
LFD	161.00	22.36

no. of CPUs: 48

Intermediate Results

- Good agreement between LFD and time domain results for the attached case
- Larger deviations for the separated case
- LFD and time domain solution should be same for small amplitudes

Aeroelasticity

(relevant to fixed-wing aircraft)

Flutter stability

Forced Response

Vibration due to flow instabilities

1. Linear Frequency Domain Solver
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Influence of transitional flows on flutter speed

Michael Fehrs
IFASD 2013

Background and Relevance

- Increasing the laminar flow regime can reduce friction drag and improve the overall flight performance.

- **But: Influence of the laminar-turbulent boundary layer transition on the aeroelastic behavior is not known.**

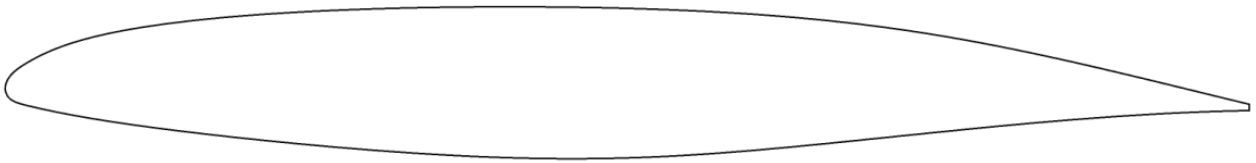
Investigation Set-up
Aerodynamic Model: CAST 10-2 Airfoil

- CAST 10-2: supercritical (laminar) airfoil

- CFD investigation with the DLR TAU code:

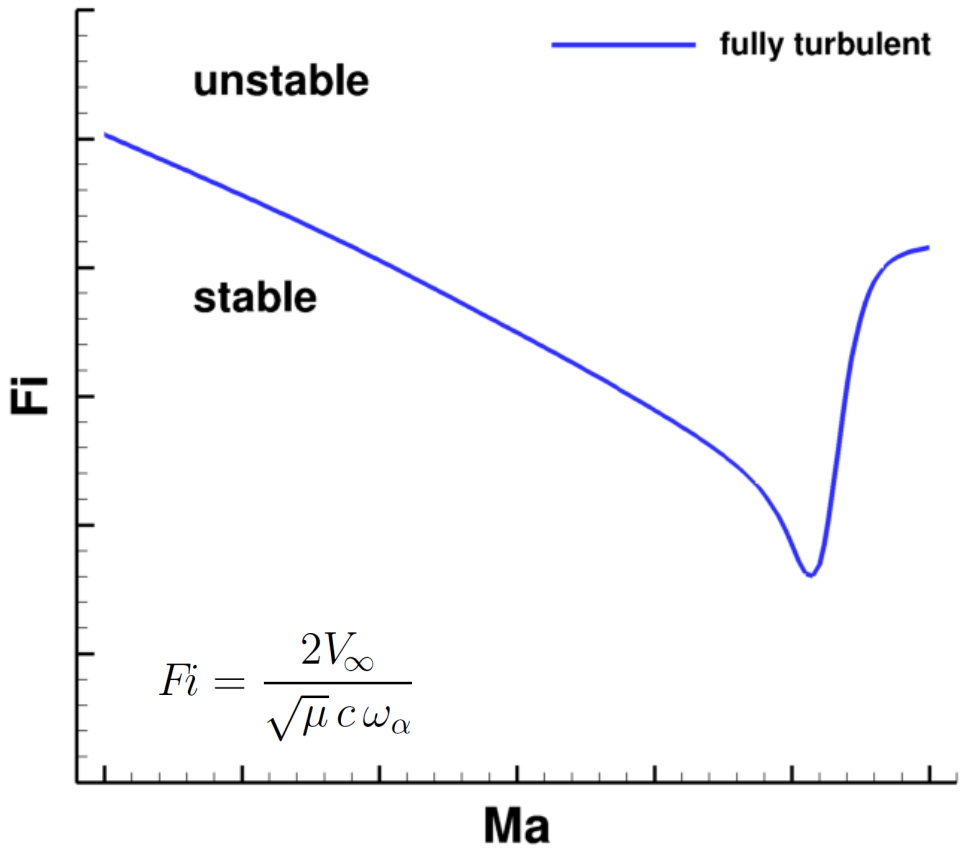
  - Ma = 0.500 up to Ma = 0.800
  - $Re_c = 2 \cdot 10^6$ with c = 0.3 m
  - unsteady analysis for $\alpha_{mean} = 0.0°$

- Wind tunnel <u>data shows large transitional regions</u> for $Re = 2 \cdot 10^6$.



Flutter Diagram

How does the flutter boundary change in a transitional flow?



Transition Modeling in CFD

RANS models and transition prediction methods

turbulence closure	transition prediction	flow type
SST k-ω model	⇨	fully turbulent flow
SST k-ω model ✚	γ-Re_θ model ⇨	transitional flow

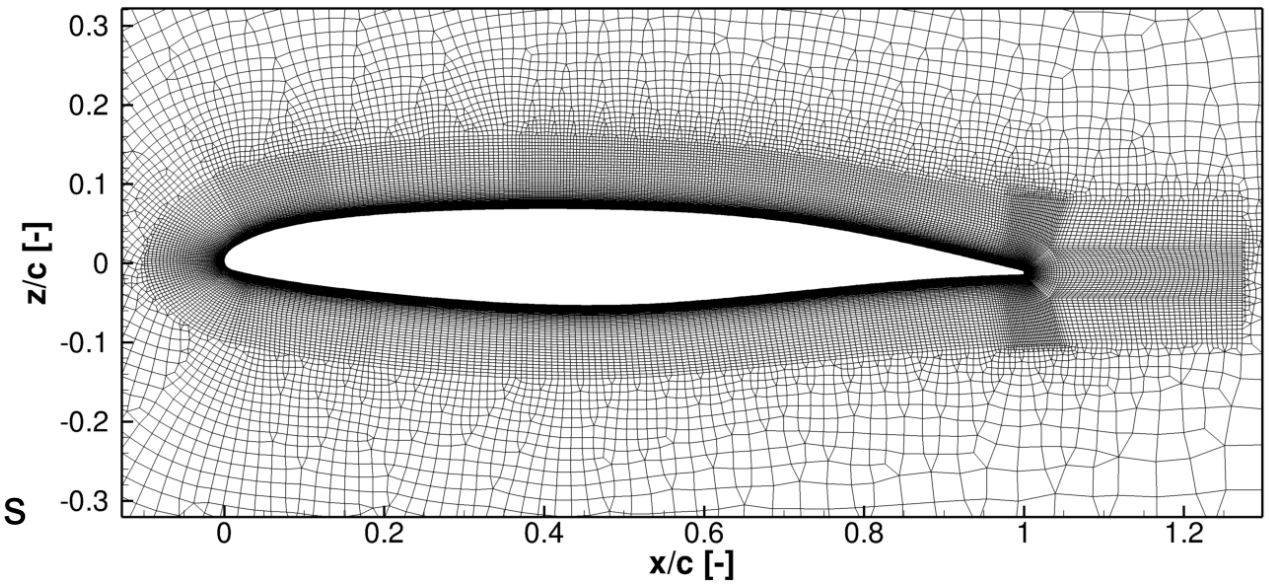
Investigation Set-up
Aerodynamic Model: CFD grid

~ 60 000 nodes

~ 290 nodes on upper surface

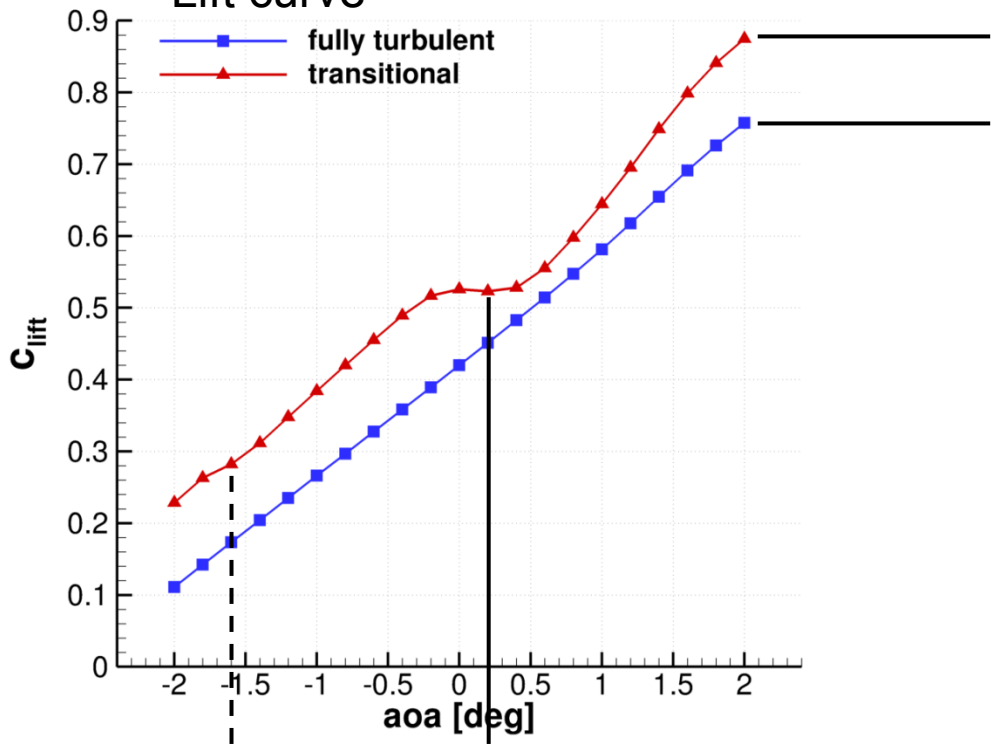
~ 210 nodes on lower surface

far field 100 chords away



Results
Steady CFD Results: Ma = 0.720

Lift curve

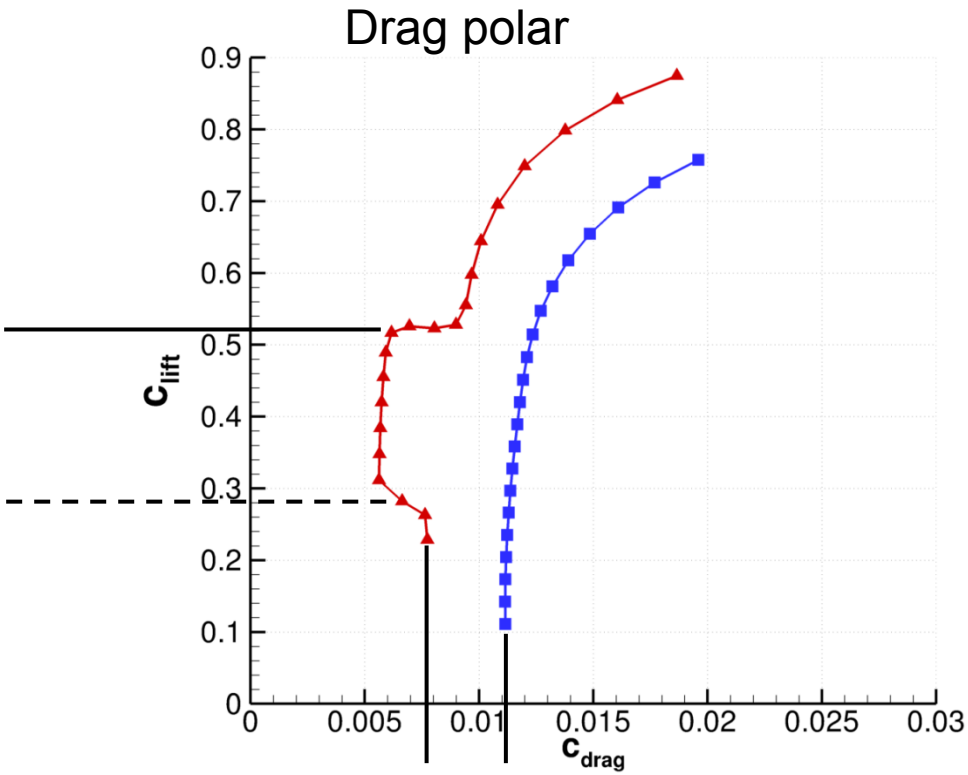


lift gain through laminar flow

non-linear lift region

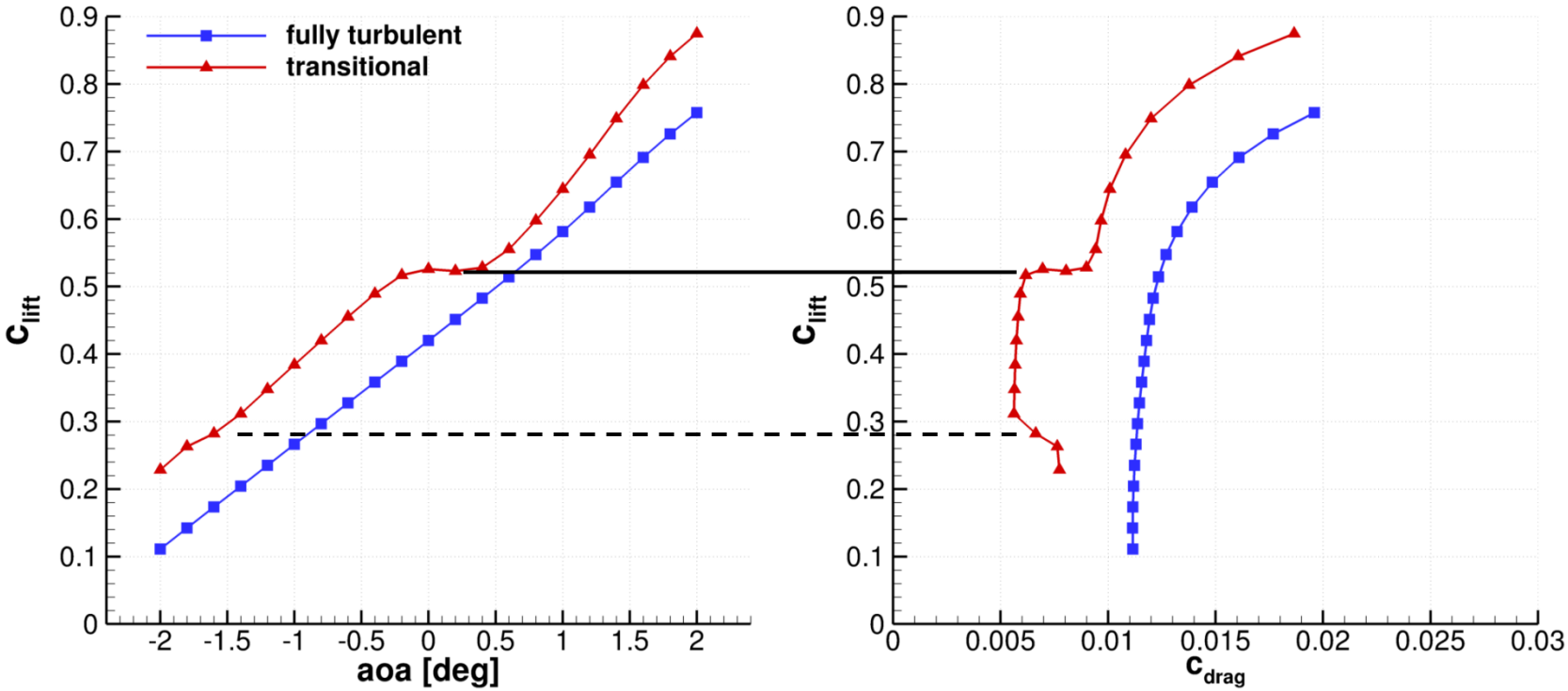
Results
Steady CFD Results: Ma = 0.720

laminar bucket



drag penalty for fully turbulent flow

Results
Steady CFD Results: Ma = 0.720



strong influence of transition behavior on lift curve

Results
Unsteady CFD results: Overview

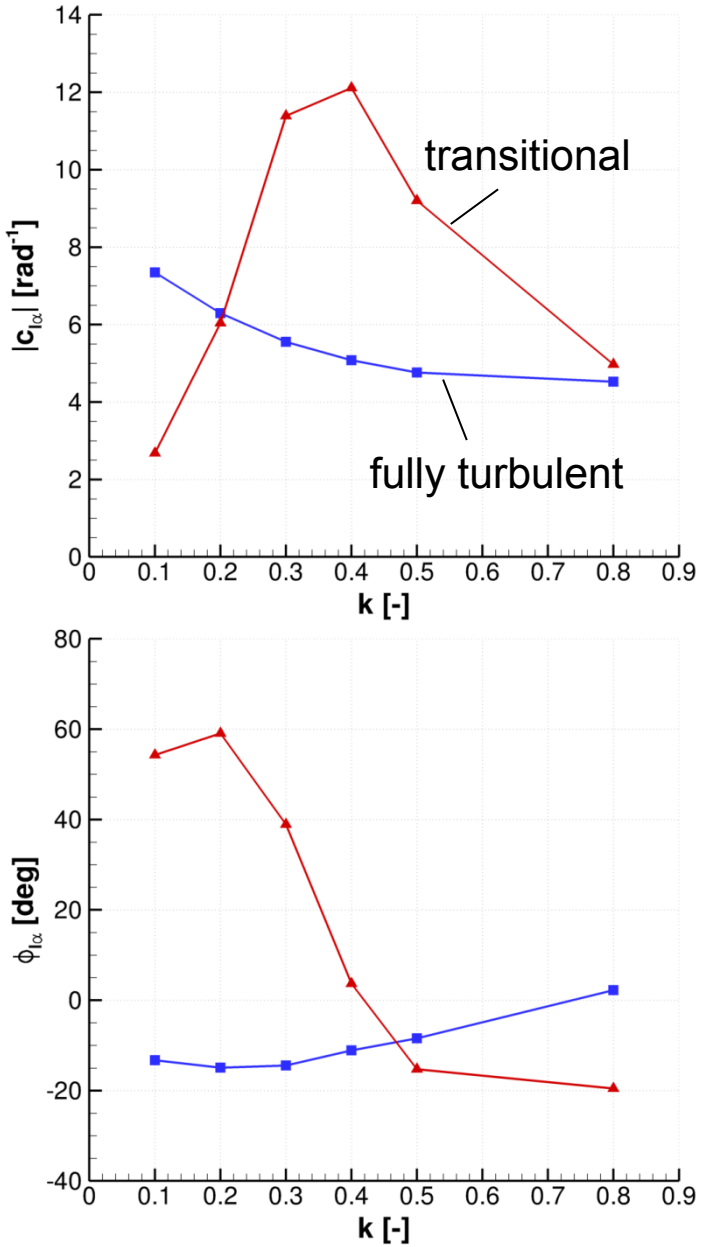
- Focus on pitch results for:
  - Mach number: 0.720
  - 6 reduced frequencies *k*
  - fully turbulent (blue) and transitional flow (red)

- Results in terms of magnitude $|c_{l\alpha}|$ and phase angle $\Phi_{l\alpha}$

Results
Unsteady CFD results: $c_{l\alpha}$

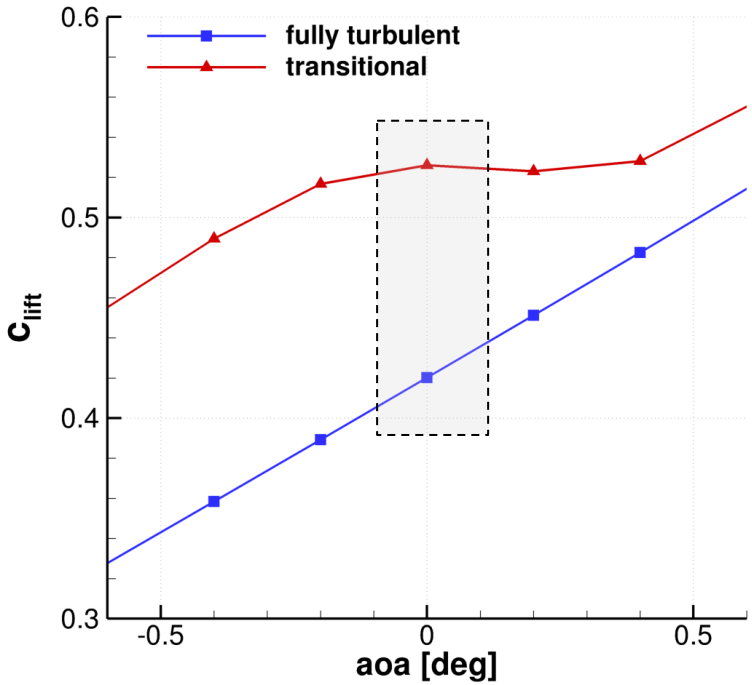
Ma = 0.720:

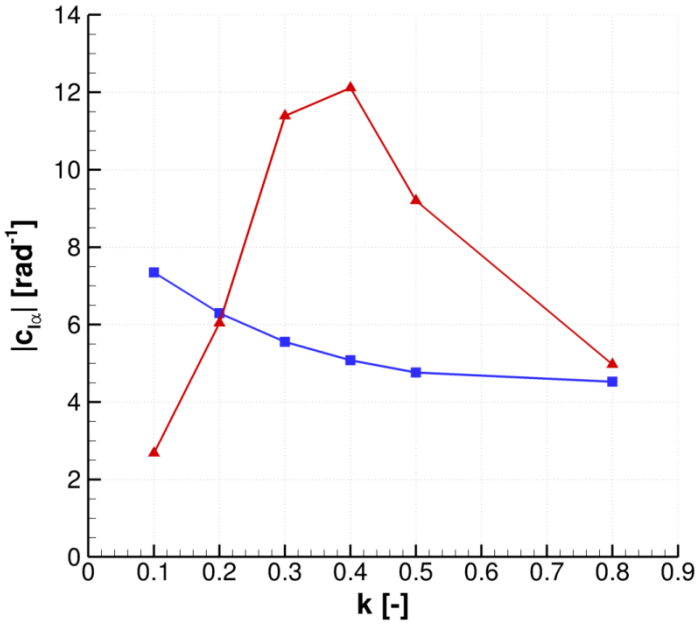
- Different magnitude and phase response for transitional flow
- Aerodynamic resonance only found for transitional flow

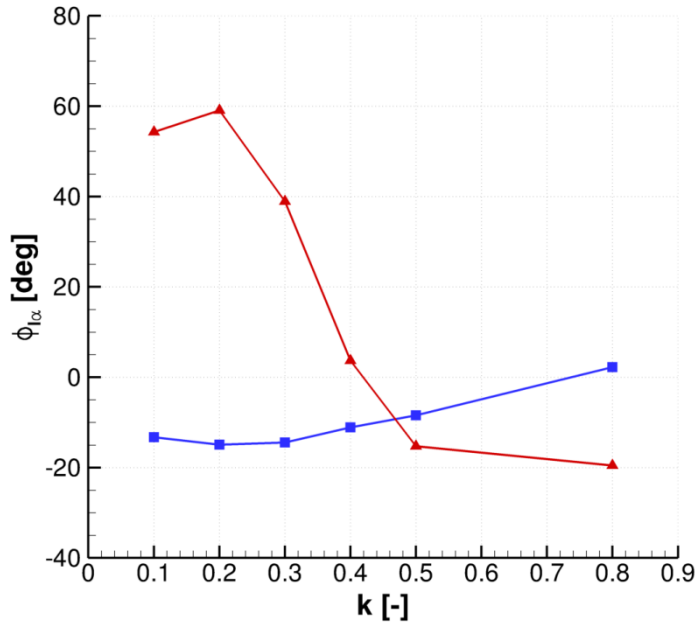


Results
Unsteady CFD results: $c_{l\alpha}$

Resonance found in the non-linear lift region



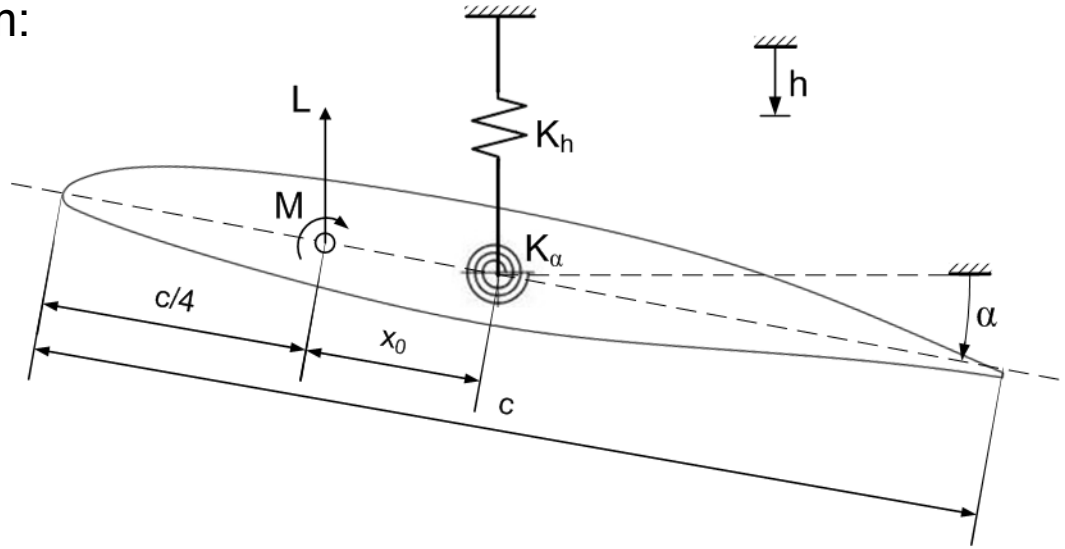




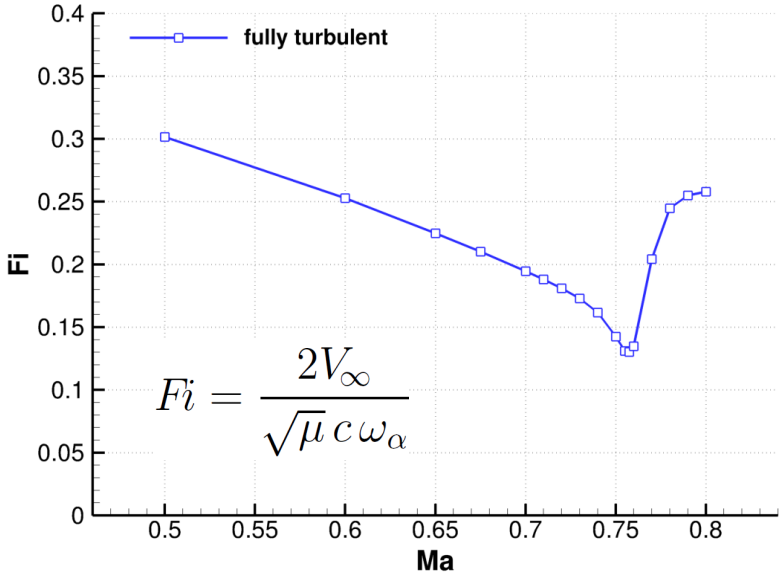
Investigation Set-up
Flutter Analysis and Structural Model

- 2 degree-of-freedom system:
  - pitch motion around quarter chord ($x_0 = 0$)
  - heave motion

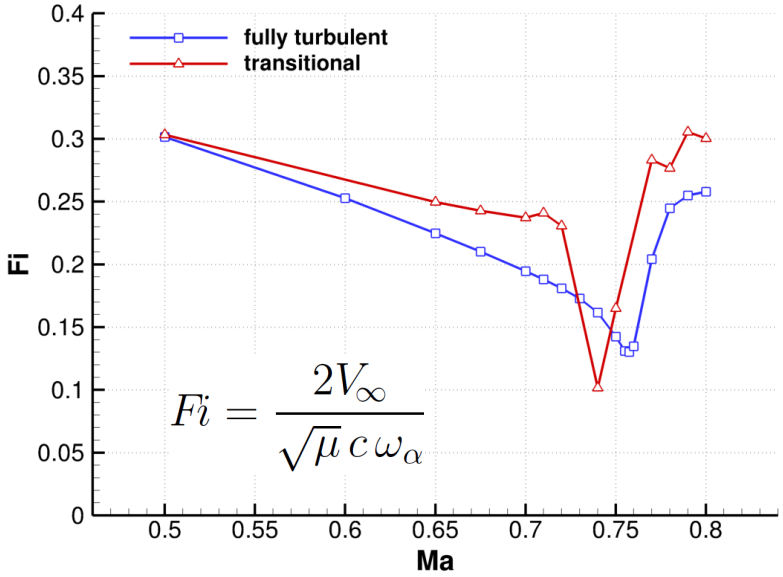
- classical bending-torsion flutter



Results
Flutter Analysis



Results
Flutter Analysis



Turbulent / Transitional flow:

- higher flutter stability for given structural model outside the transonic dip with BL transition
- but deeper transonic dip at lower Mach number with BL transition

Intermediate Results

- CFD based flutter analysis for a supercritical airfoil (CAST 10-2):
  - Fully turbulent and transitional simulations
  - Re = 2e6, transonic flight regime
- **The transonic dip gets deeper and moves to a lower Mach number for a transitional flow.**
- **The transitional flows show an aerodynamic resonance connected to an instability of the transitional region.**
  - For the transitional flows the magnitude and phase response to the prescribed motion differ significantly from the turbulent ones.
  - A similar resonance is found in wind tunnel data.

Future Work

- **Comparison to wind tunnel data from ongoing experiments with the CAST 10-2 airfoil at the DLR.**

- **Validation of the transition model's prediction capabilities for unsteady transonic flows.**

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(relevant to fixed-wing aircraft)

Flutter stability

Forced Response

Vibration due to flow instabilities

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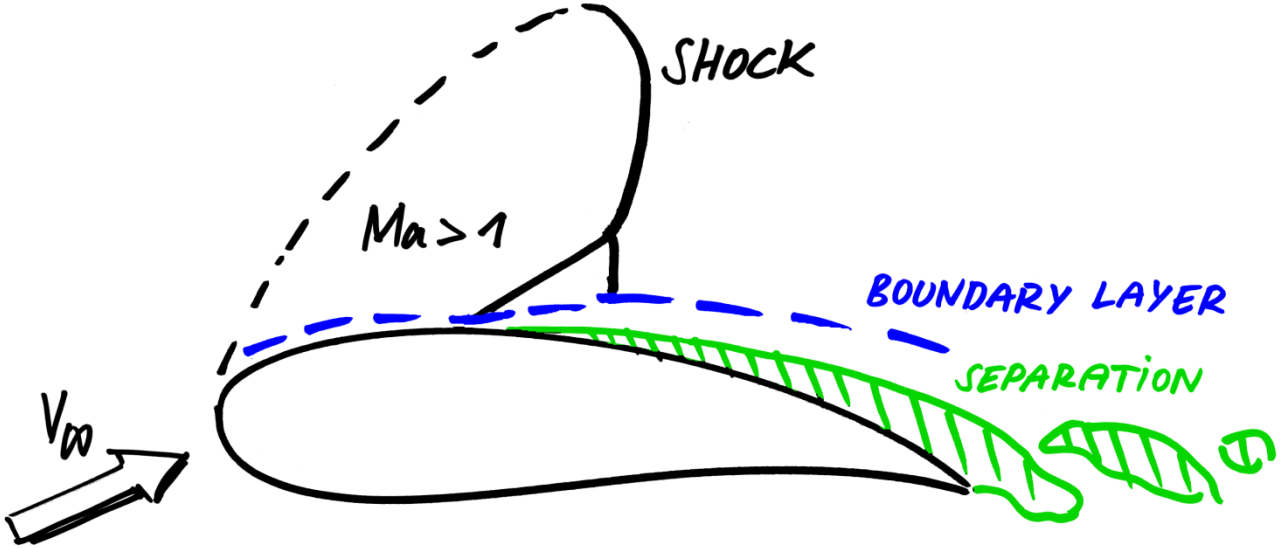
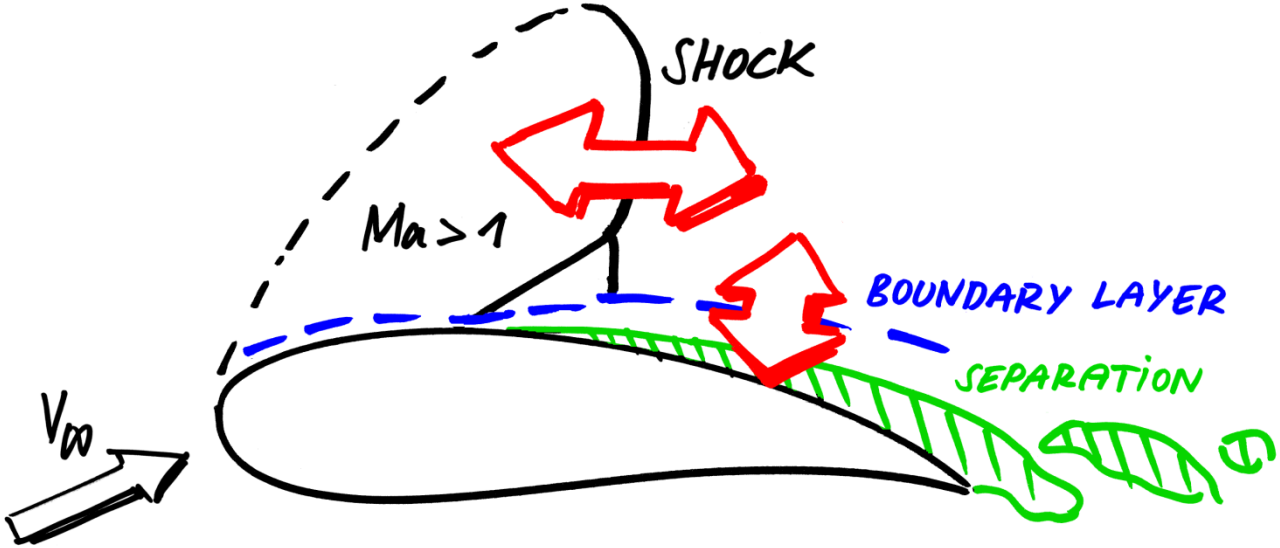
DLR

Shock Buffet

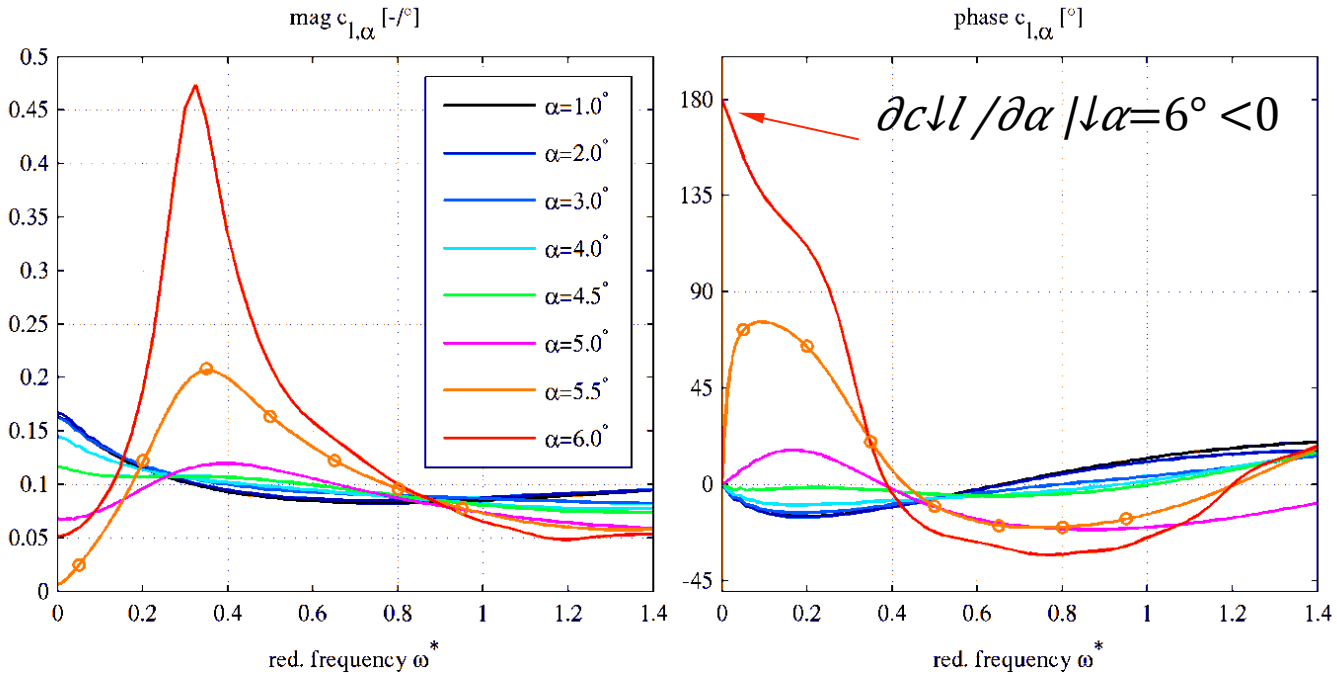
Jens Nitzsche
STAB 2012


SHOCK
Ma > 1
BOUNDARY LAYER
SEPARATION
V_∞

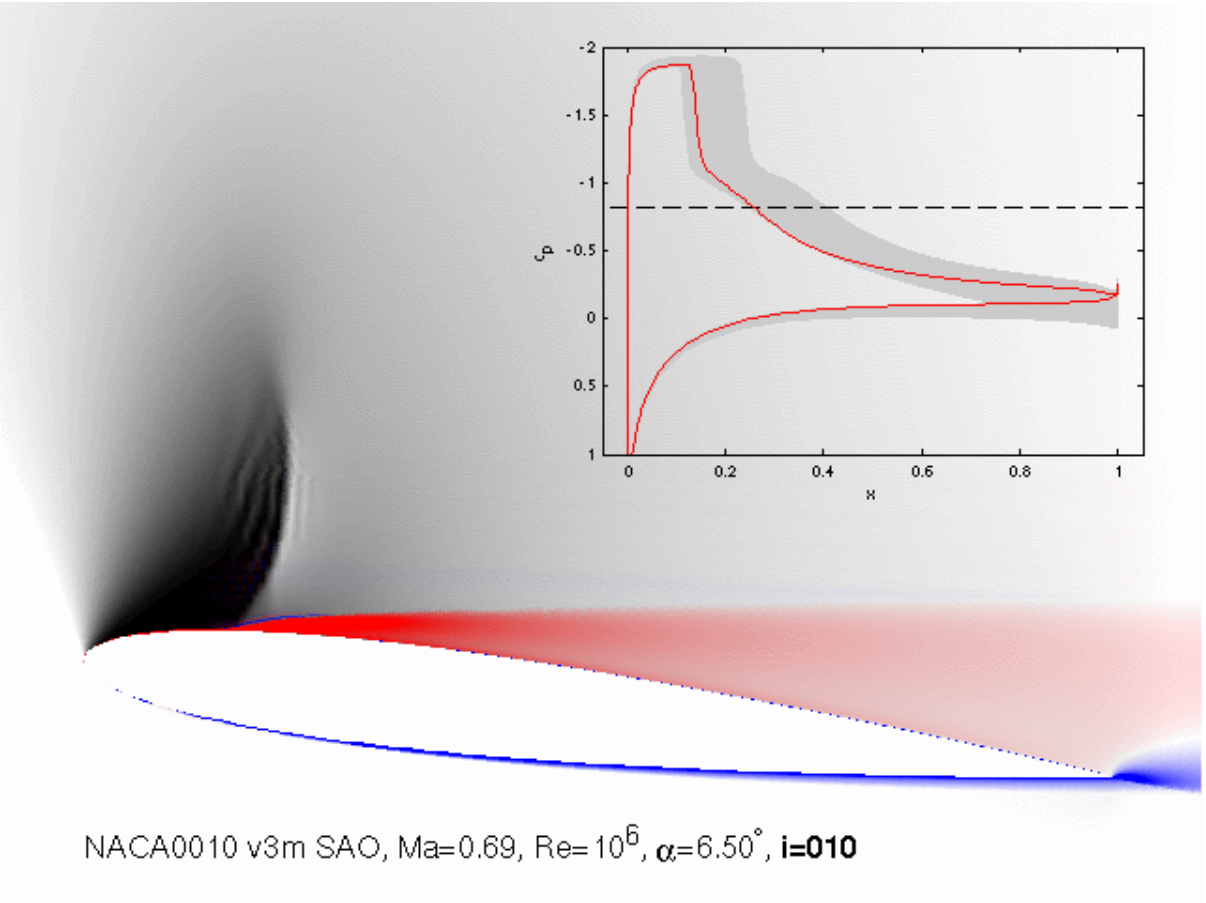

SHOCK
Ma > 1
BOUNDARY LAYER
SEPARATION
V_∞

Shock Buffet

- **NACA0010**, Ma=0.69, Re=10×10^6, 2-d (U)RANS, SAO
- Pitch around c/4

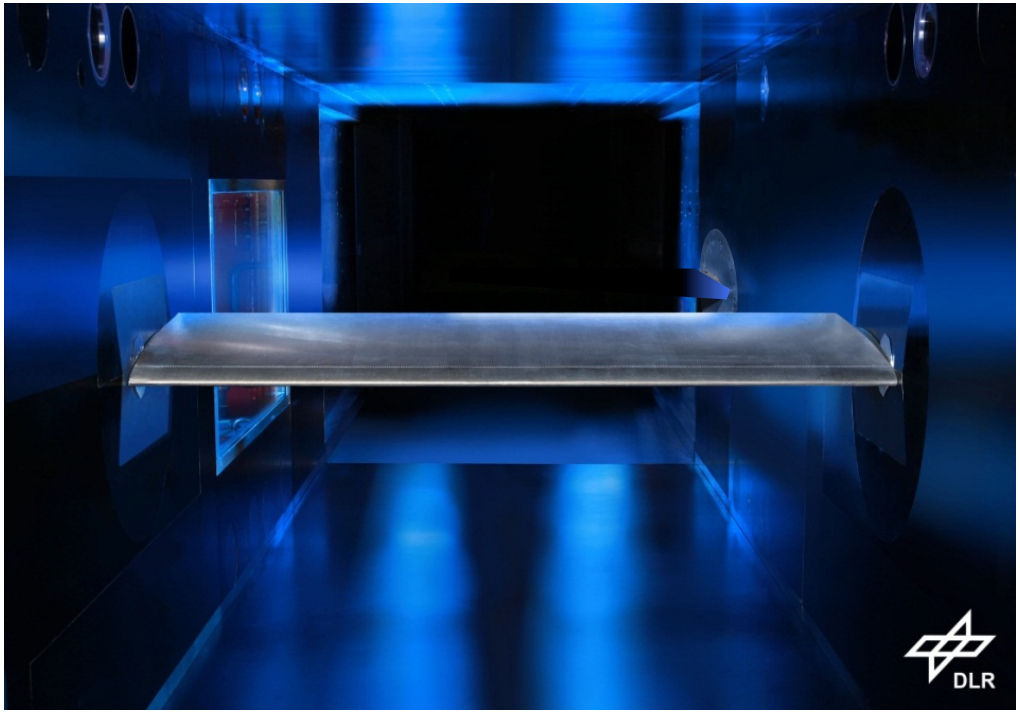


Shock Buffet
Aerodynamic Resonance

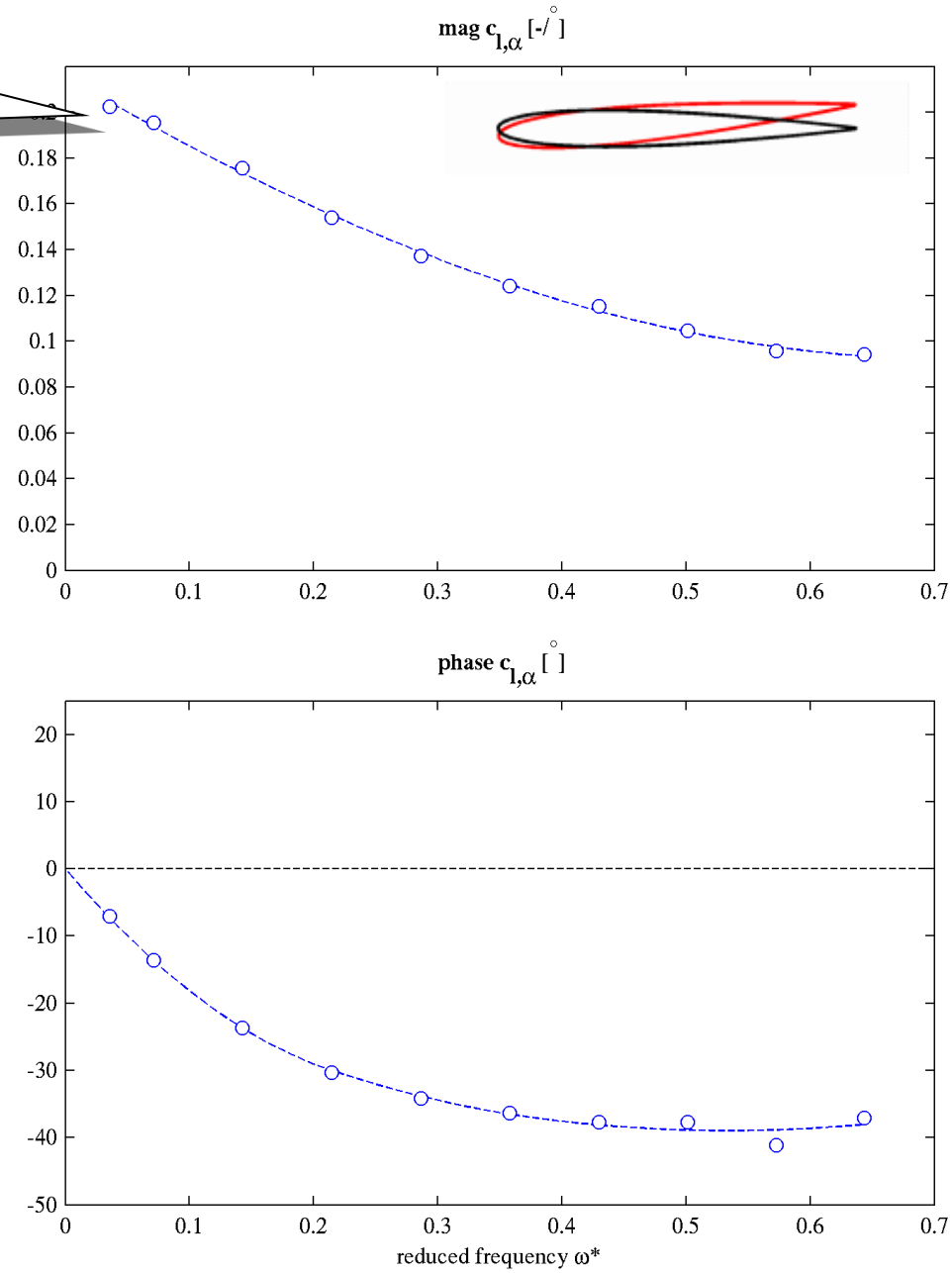


Shock Buffet

Experiment in Transonic Windtunnel Göttingen (TWG):



Ma 0.80
Re 1.95×10⁶



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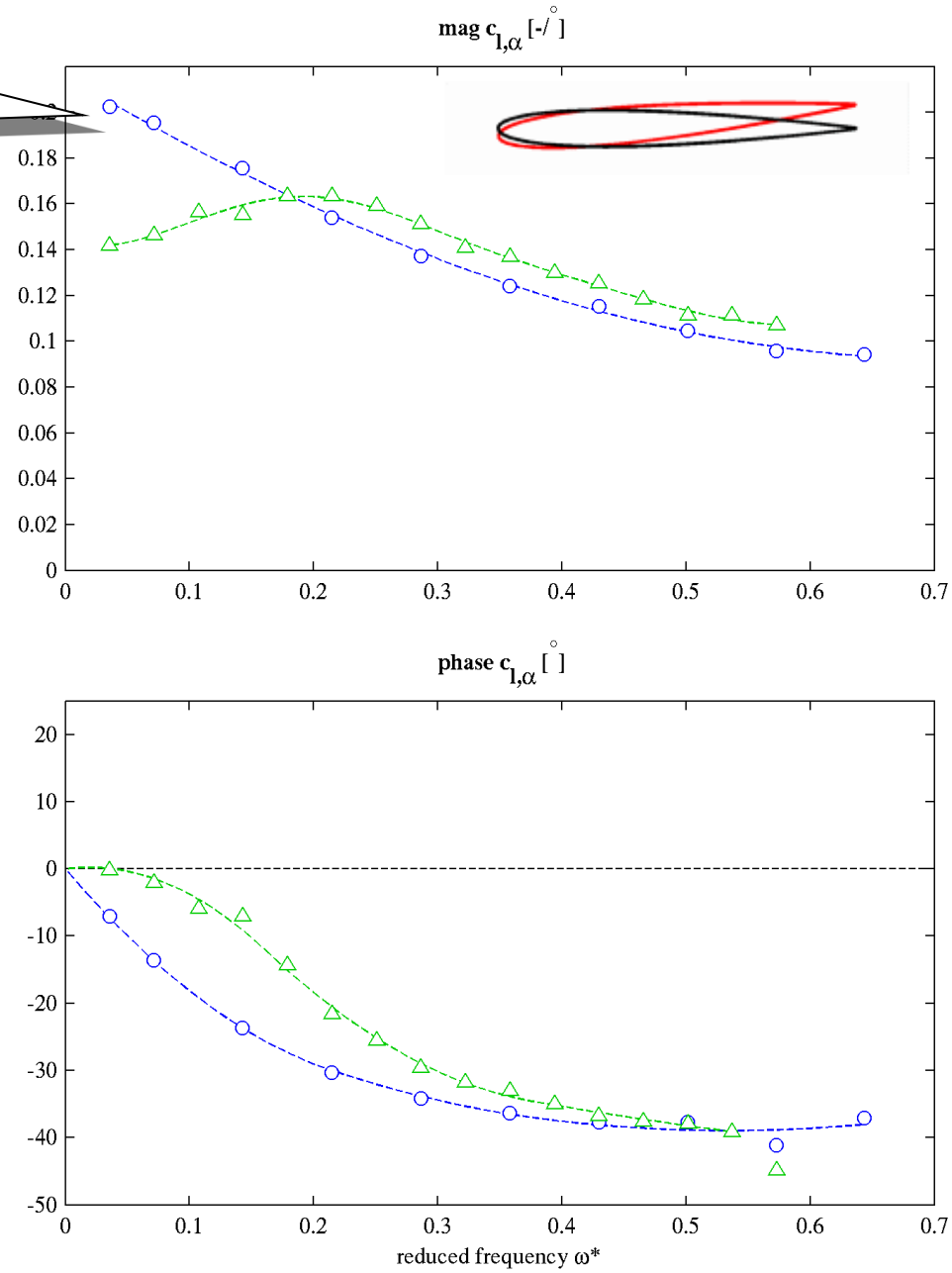

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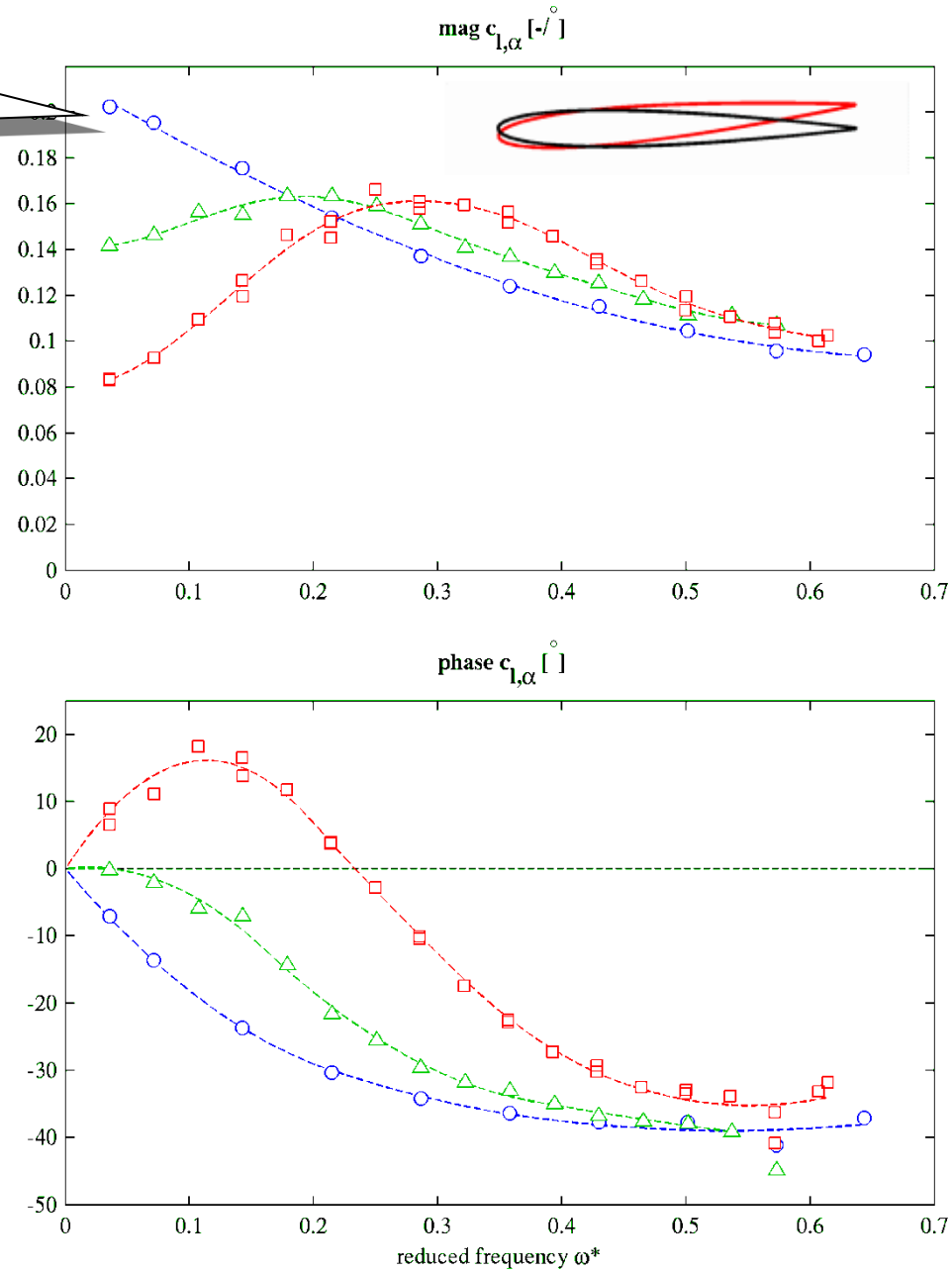

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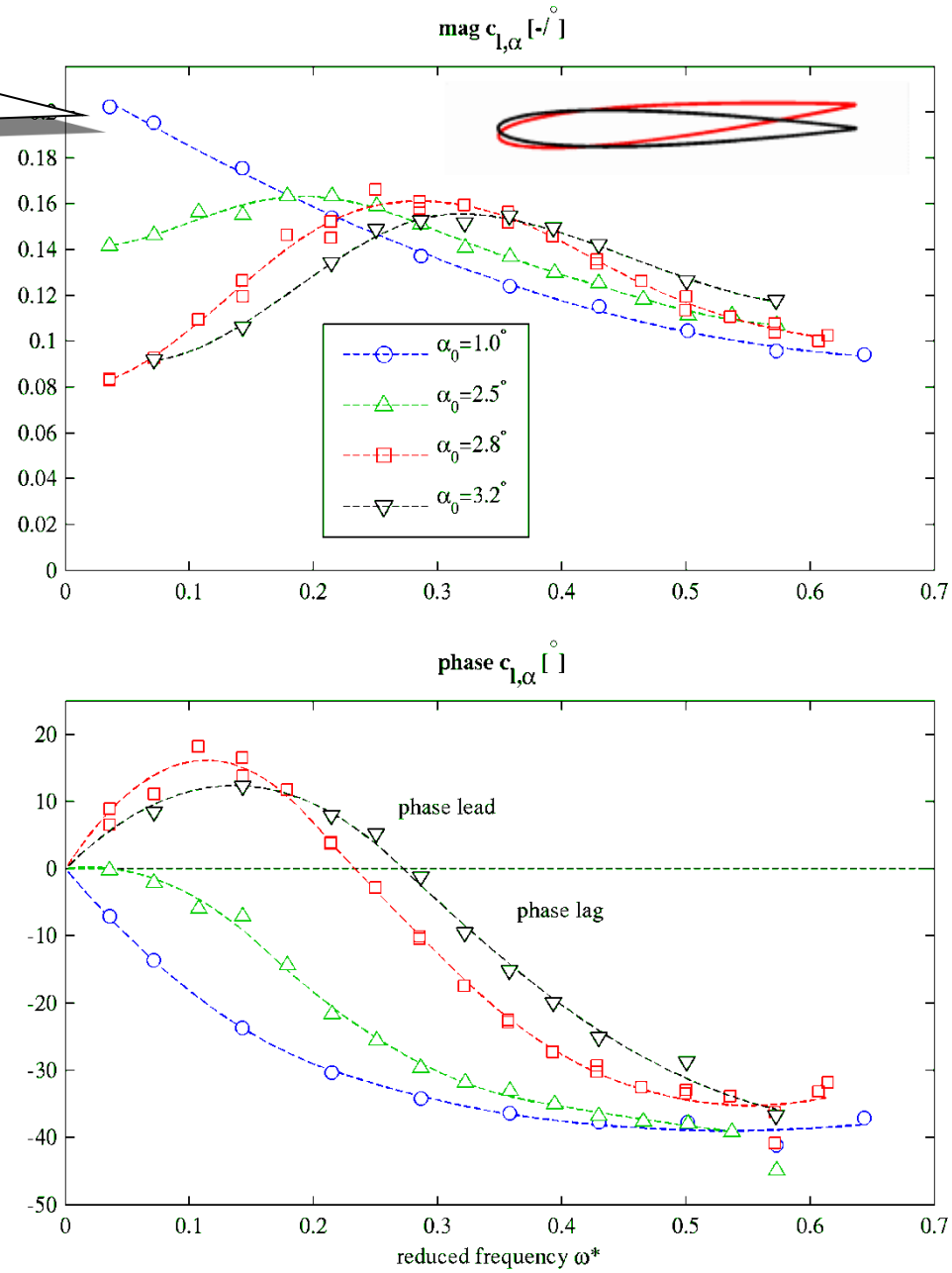

Deduction

Shock buffet onset problem
seems to be treatable as a linearized stability problem

Aeroelasticity

(relevant to fixed-wing aircraft)

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DLR

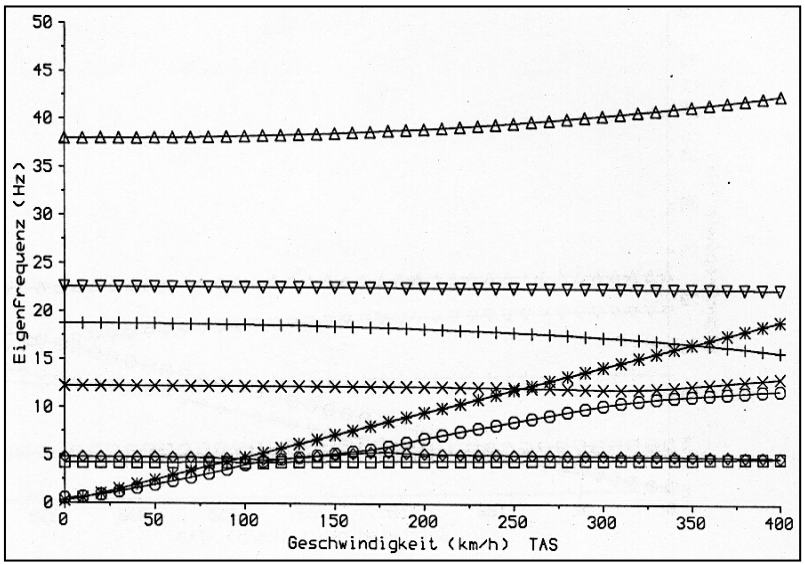
Flutter Analysis

Fast and Reliable Flutter Analysis

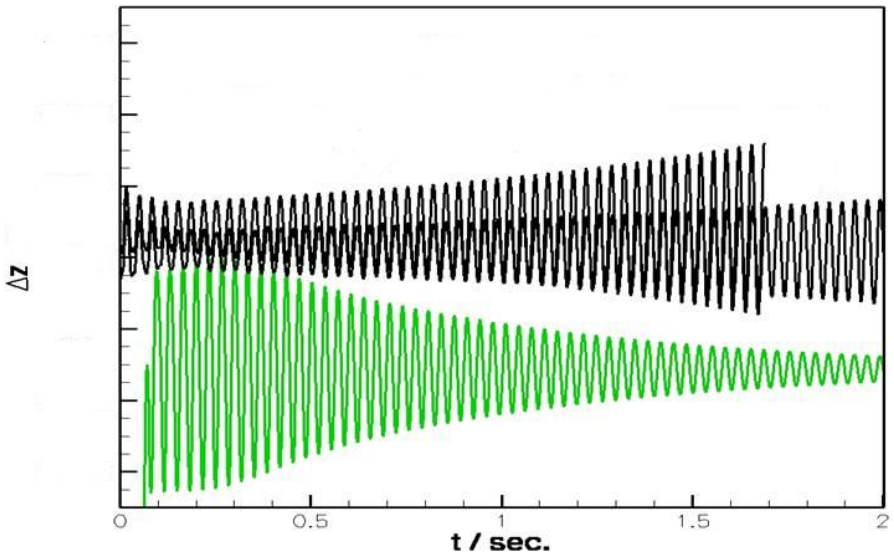
Challenges

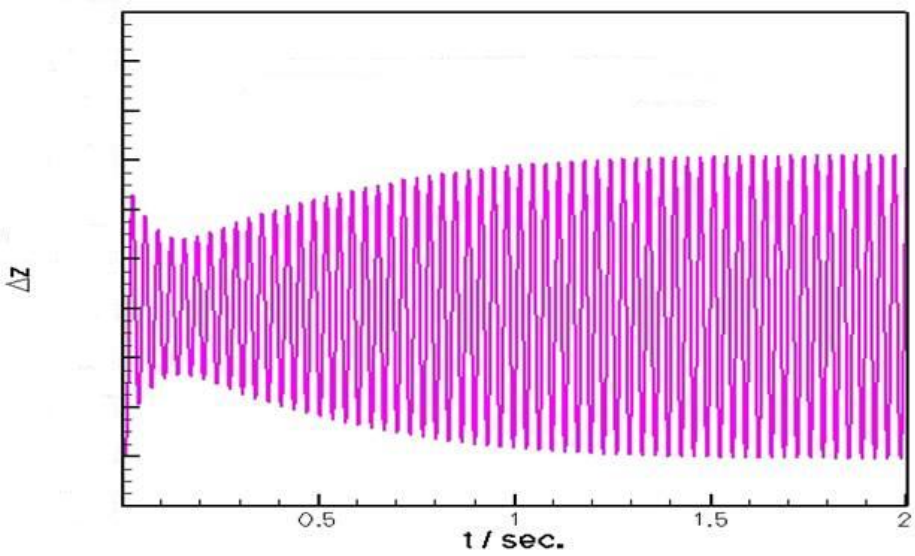
- Applicability of validated CFD methods to a/c design and aeroelastic certification process

- Analyze aeroelastic stability in full operational and flight domain by frequency domain methods
  - High number of flight conditions, load cases, modes, reduced frequencies, …
  - Generalized airloads calculation as fast as by DLM
  - Identify critical couplings & conditions



Fast and Reliable Flutter Analysis





- Simulations in time-domain to identify influence of nonlinearities at selected flight conditions
  - from structure, or controls laws
  - from aerodynamics

Fast and Reliable Flutter Analysis for Complete Aircraft

Strategies

1. Reduction of CPU time for CFD runs
   - Massive parallelization of process running nonlinear CFD
   - Time-linearized RANS
   - Reduced order modelling (ROM)
     - DLM correction methods
2. Efficient approximation methods models to investigate structure and system nonlinearities in time-domain
3. Uncertainty analysis methods
4. Combination of strategies 1 to 3

Conclusion

Linear Frequency Domain Solver
validated for attached case

Laminar Flow, Flutter Speed
transonic dip deeper and at a lower Mach

Shock Buffet
treatable as a linearized stability problem

Flutter Analysis
reduction of CPU time