Introduction to the HIRENASD Experiments

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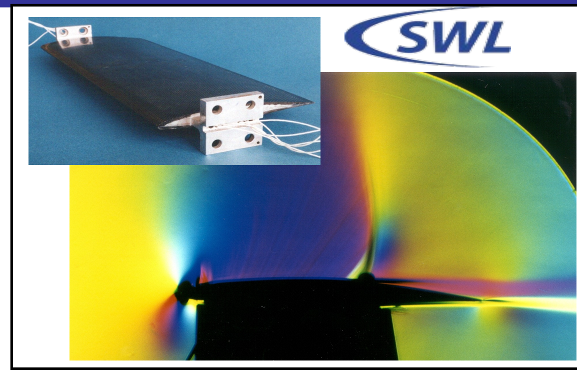
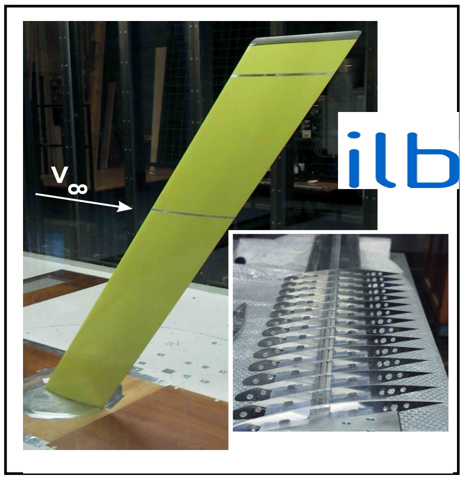
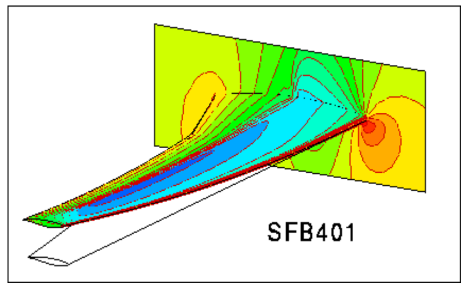
Aachen University / ITAM GmbH

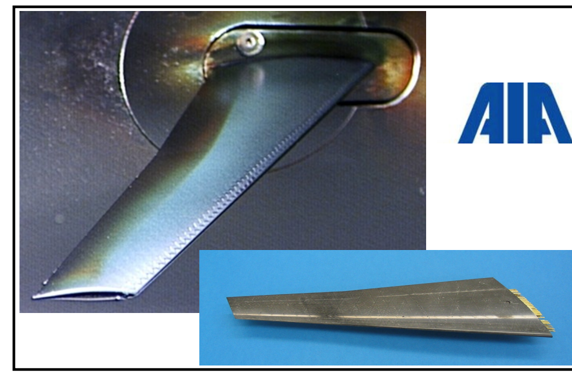
SFB 401: ***Modulation of Flow and Fluid-Structure Interaction at Airplane Wings***

Aeroelastic Research at Aachen University

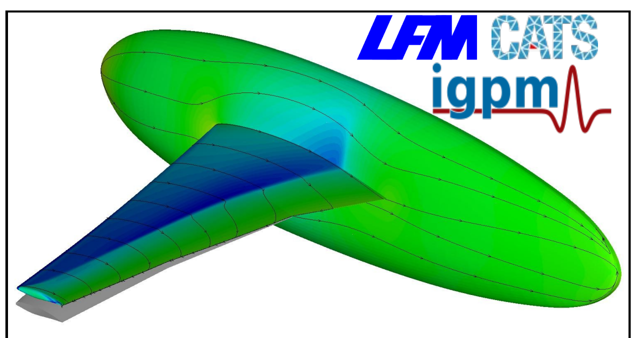








Collaborative Research Center *SFB 401*



ASD Simulation Method: Partitioned Approach

- **Aeroelastic time-domain simulations**

- **Stationary and Non-Stationary Flow:**

- FLOWer (DLR), RANS
- Multi-block-structured FV code
- Dual-time-stepping (unsteady mode), 5-stage RK (steady mode)

- **Structure Deformation:** Reduced-order modeling preferred for the structure:

- Multi-axial Timoshenko beam model
- Modal time integration preferred over direct time integration

- **Grid deformation:**

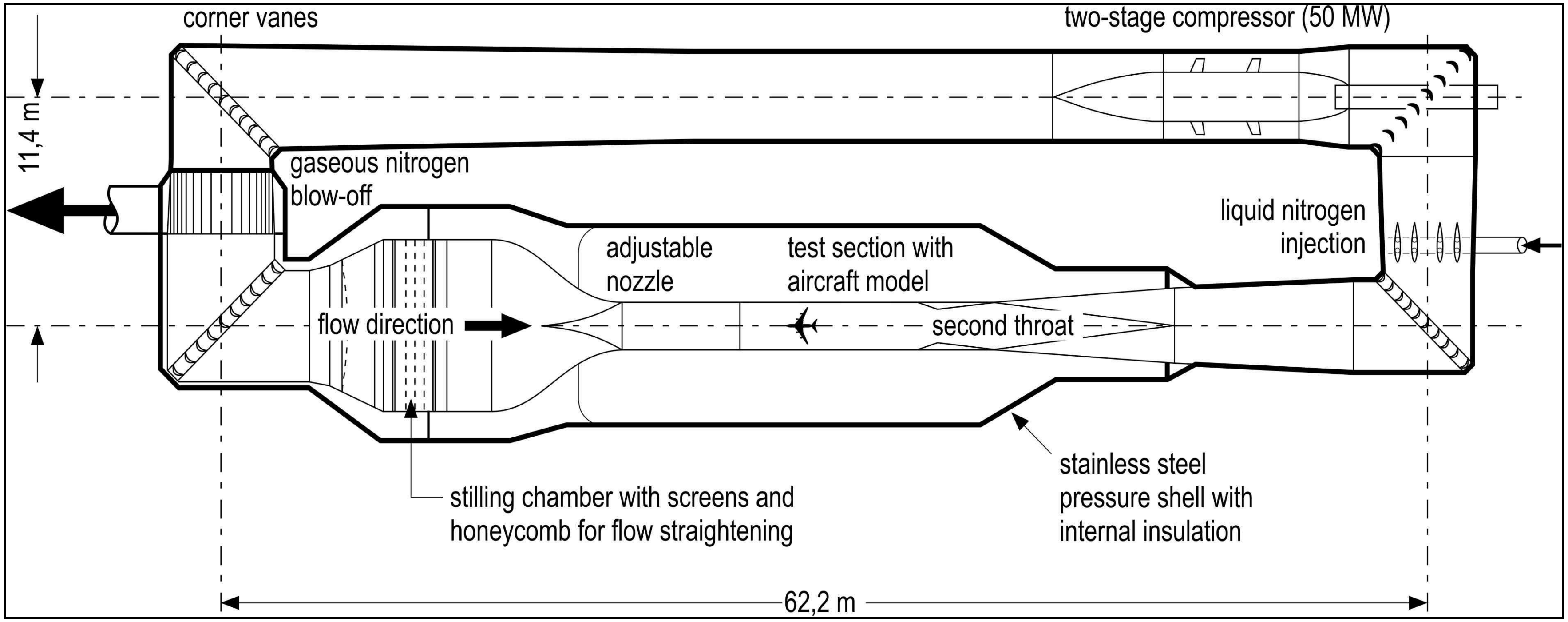
- Mixture between structural analogy & algebraic interpolation:
- Beam framework for block topology
- Algebraic interpolation inside blocks

- **Spatial FSI coupling:**

- Rigid link between CFD point & next CSM element
- Finite interpolation elements for conservative load & deformation interpolation
- Blending/interpolation techniques: non-unique mappings & surface joints

European Transonic Windtunnel (ETW)

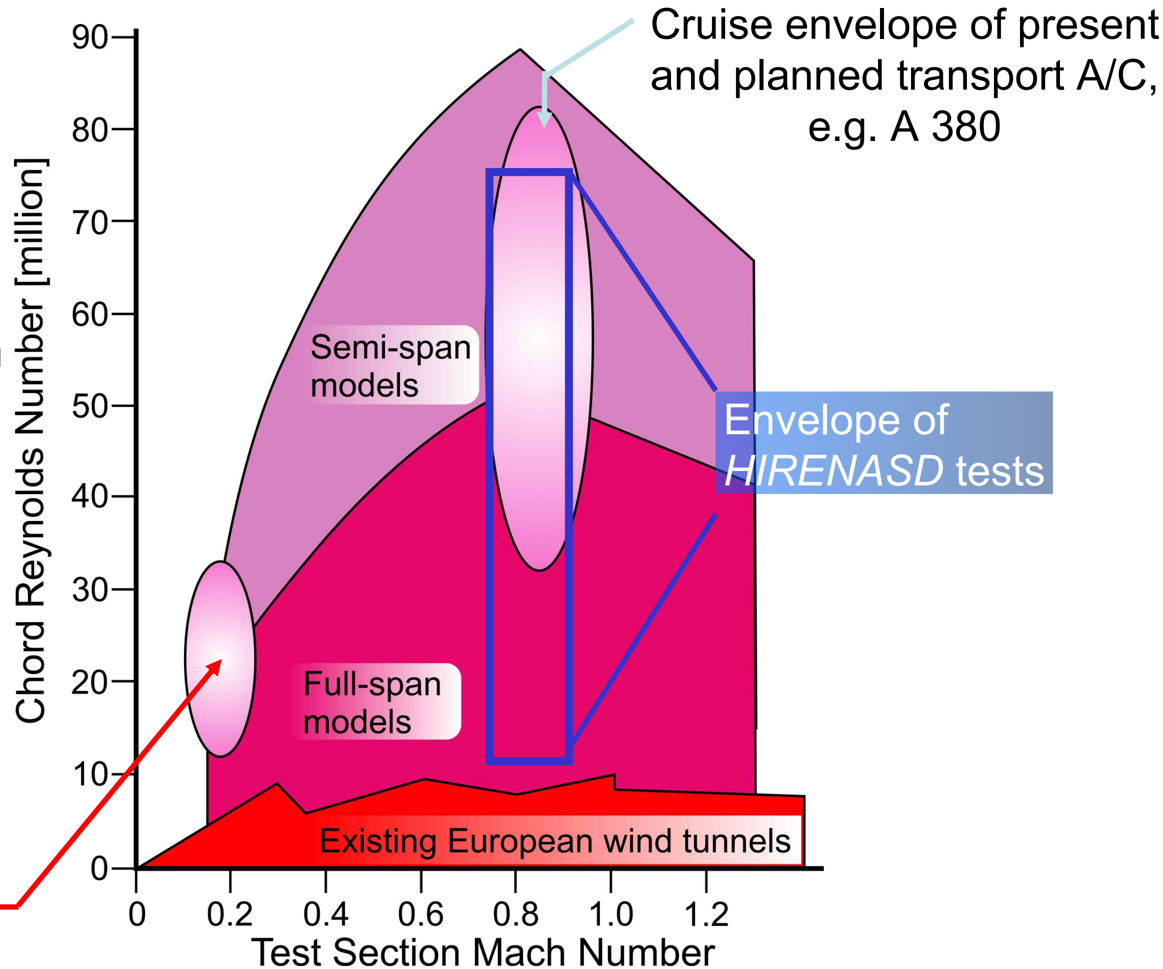
- Fluid temperature: 110K – 313K
- Pressure: 1.25bar – 4.5bar
- Fluid: Nitrogen gas
- Test section dimensions:
  - Height: 2.0m
  - Width: 2.4m
  - Length: 9.0m



European Transonic Windtunnel (ETW)

High Reynolds Number in WT Experiments

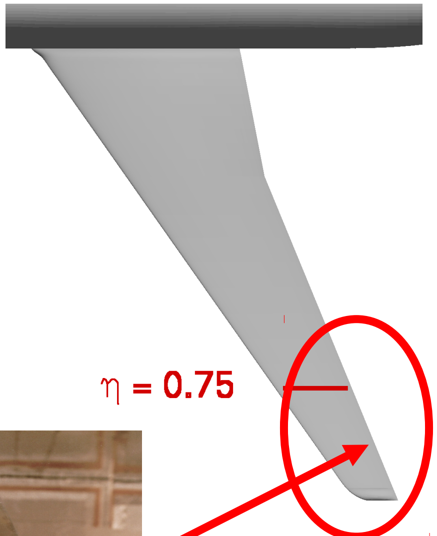
Re = v∞ **cref** ρ∞ /μ,
sgn Δμ = sgn ΔT,
sgn Δ ρ = sgn Δ p
⟹ Test gas temperature down (to e.g. 120 K) and total pressure up
⟹ Aerodynamic force onto model in the range of tons
⟹ **Wing model deforms considerably,**
⟹ **flow field and pressure distribution affected**

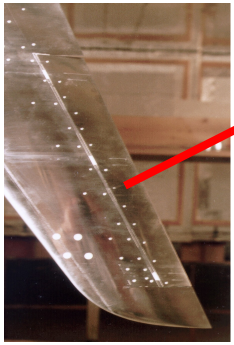


Independent setting of *Ma*, *Re* and total pressure p_t enables separation of **aerodynamic** and **aeroelastic/load** effects characterised by **q** and ratio **q/E**

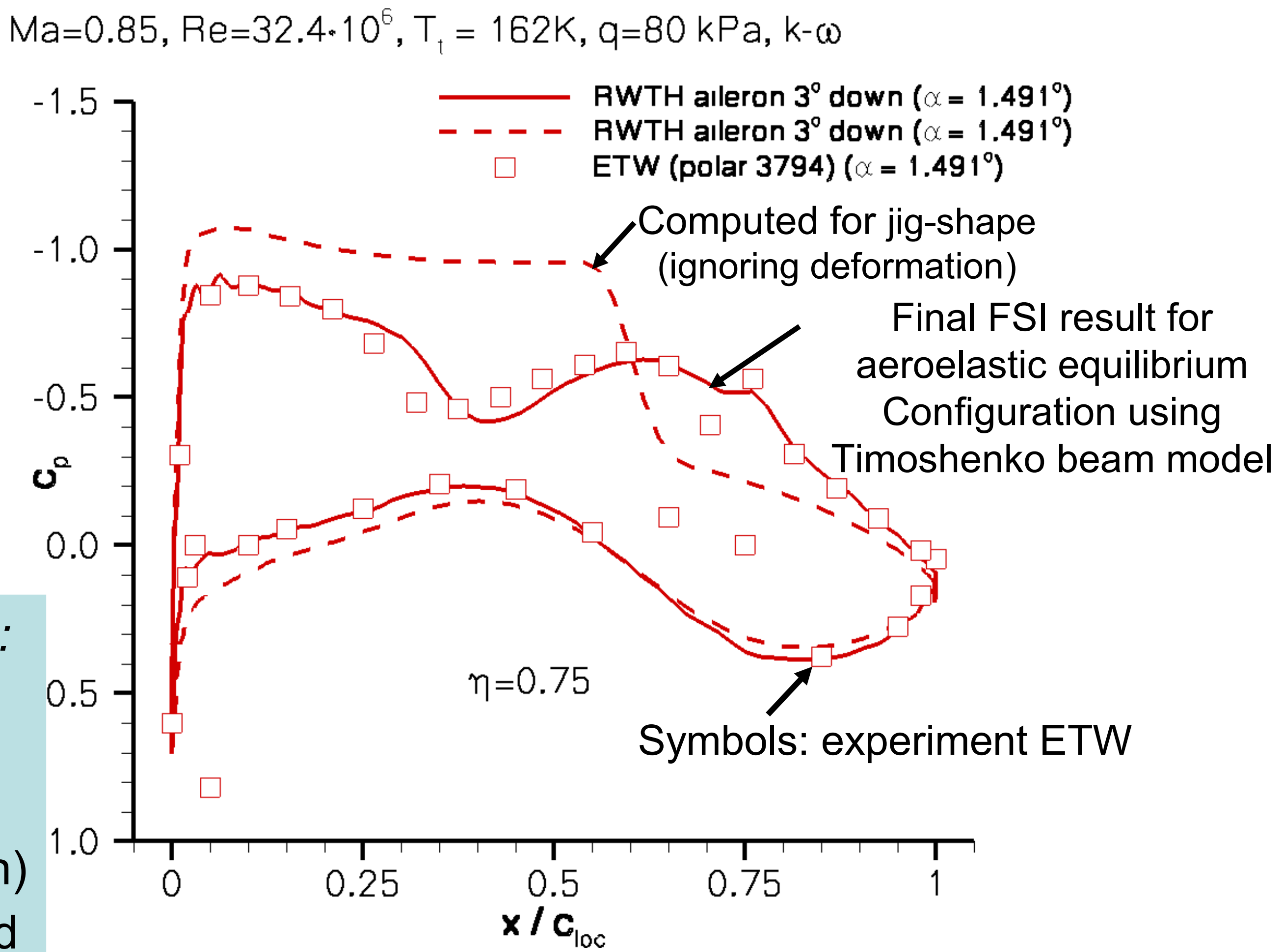
Example: Aeroelastic Equilibrium Configuration in ETW

Pressure distribution: rigid wing ↔ flexible wing (real experiment)





Flow conditions:
Ma = 0.85
Re = 32.5 M
q_∞ = 80000 Pa
c_l = 0.5 (=design)
aileron deflected



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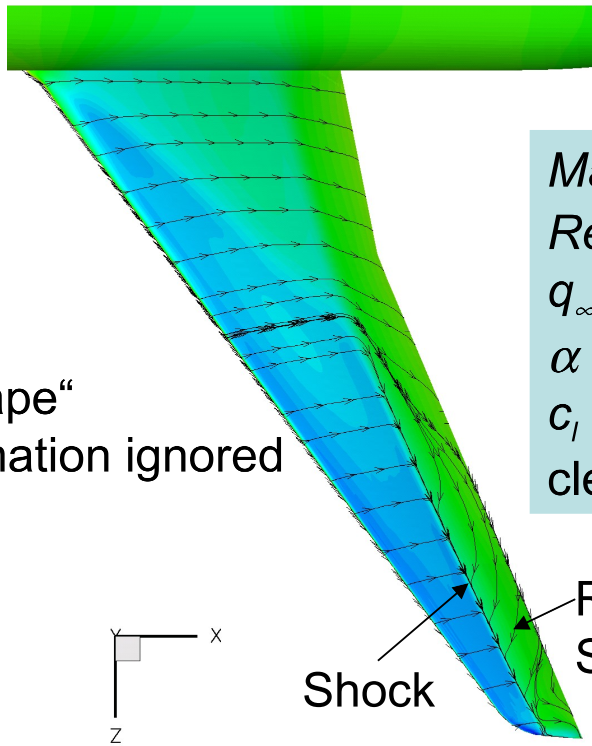
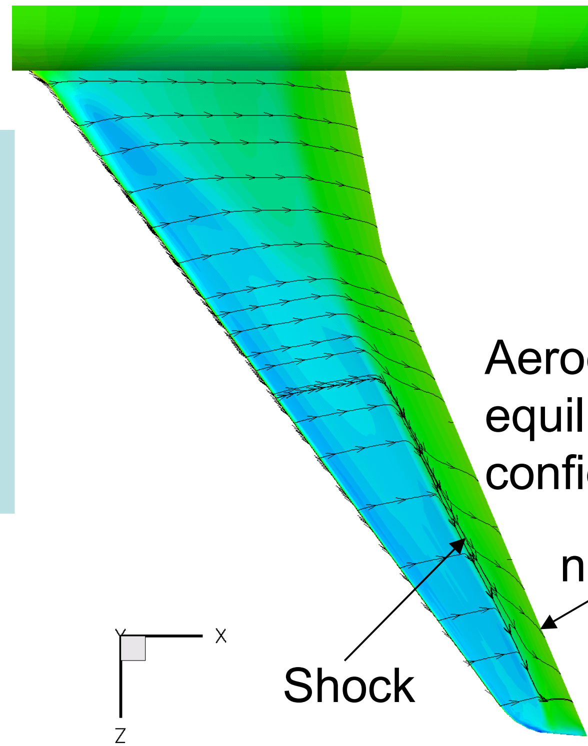
HiReTT: Aeroelastic Equilibrium Configuration

Effect of wing deformation on flow pattern on wing surface

„jig shape“
Deformation ignored



$Ma = 0.85$
$Re = 32.5 \cdot 10^6$
$q_\infty = 80000$ Pa
$\alpha = 2{,}5054°$
$c_l = 0.67$
clean wing



Wing tip:
$\Delta\alpha = -\varphi_{z,wingtip} = -2.3°$

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Lessons Learned from the Real Experiment

- Significant wing deformation in High Reynolds number wind tunnel testing, **force parameter q replaced by q/E, E Young's modulus of WT model**
- Evaluation of test data w.r.t. Re number not simple $\rightarrow$ wing deformation must be considered at same time
- No chance for pure CFD methods

- Beam model sufficient for slender wing to predict the influence of shape change on aerodynamic properties
- Computational effort: CPU-time CFD $\approx$ CPU-time CFD+CSM
- Very good agreement with experimental data

Disadvantage for university research w.r.t. industrial experiments: No free access to data and no publication of experimental data in physical units

HIRENASD

Main objectives of the project

High **Re**ynolds **N**umber **A**ero-**S**tructural **D**ynamics (***HIRENASD***)

1. To improve ASD knowledge and gather experimental data

- for transonic flow about an aircraft type wing model in a wide range of loads (expressed in terms of *q/E*),
- for Reynolds numbers up to the range of large aircraft in cruise,

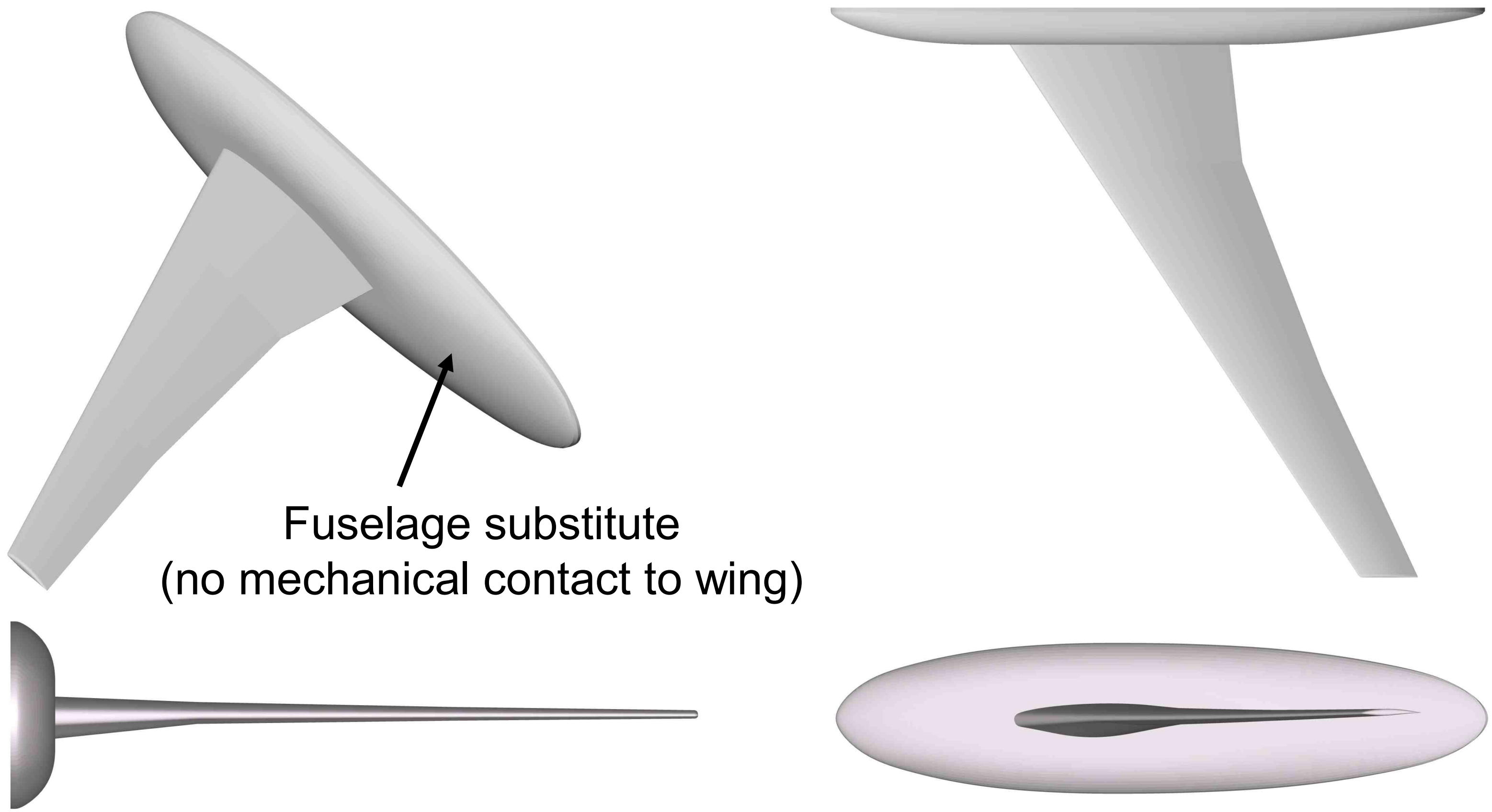
with emphasis on

- aeroelastic equilibrium configurations
- aero-structural dynamic processes
- aerodynamic damping mechanisms
- unsteady shock/boundary-layer interaction
- unsteady flow separation

2. To provide experimental data in a data base that is freely accessible to universities for transonic aeroelastic research, modeling enhancement, and validation of aeroelastic and aerodynamic numerical methods as well.

Design Views on HIRENASD Wind Tunnel Model

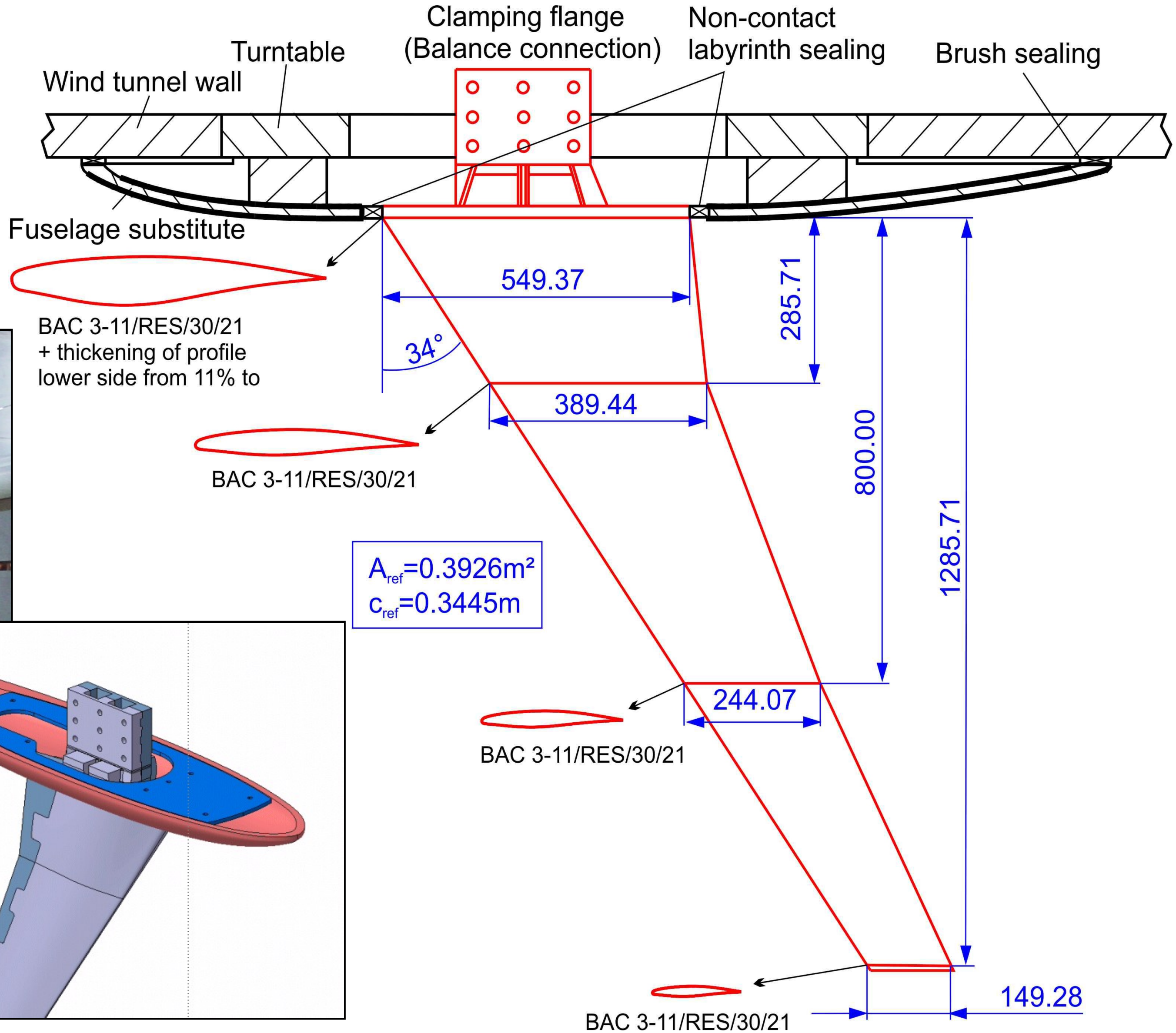
Geometry of *HIRENASD* Windtunnel Model:

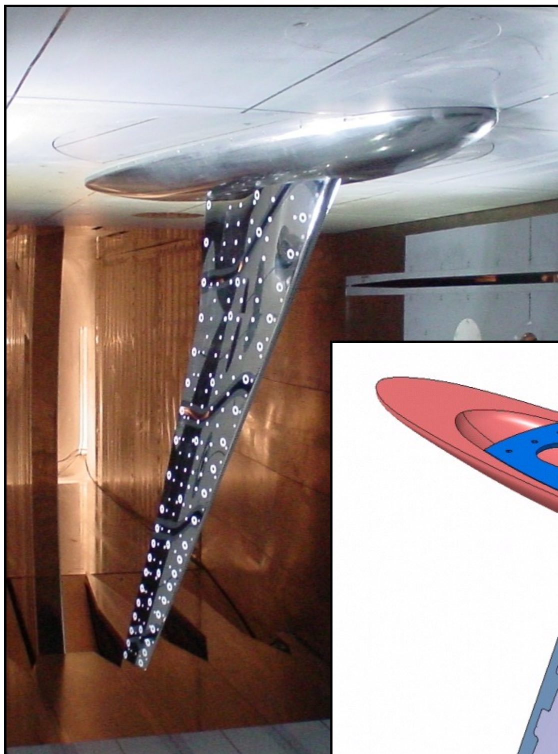


Wing geometry is a 1:28 scale model of the *SFB 401* reference configuration.
Span of the 1:1 size corresponds to aircraft A380

HIRENASD Windtunnel Model and Assembly

Model Dimensions:





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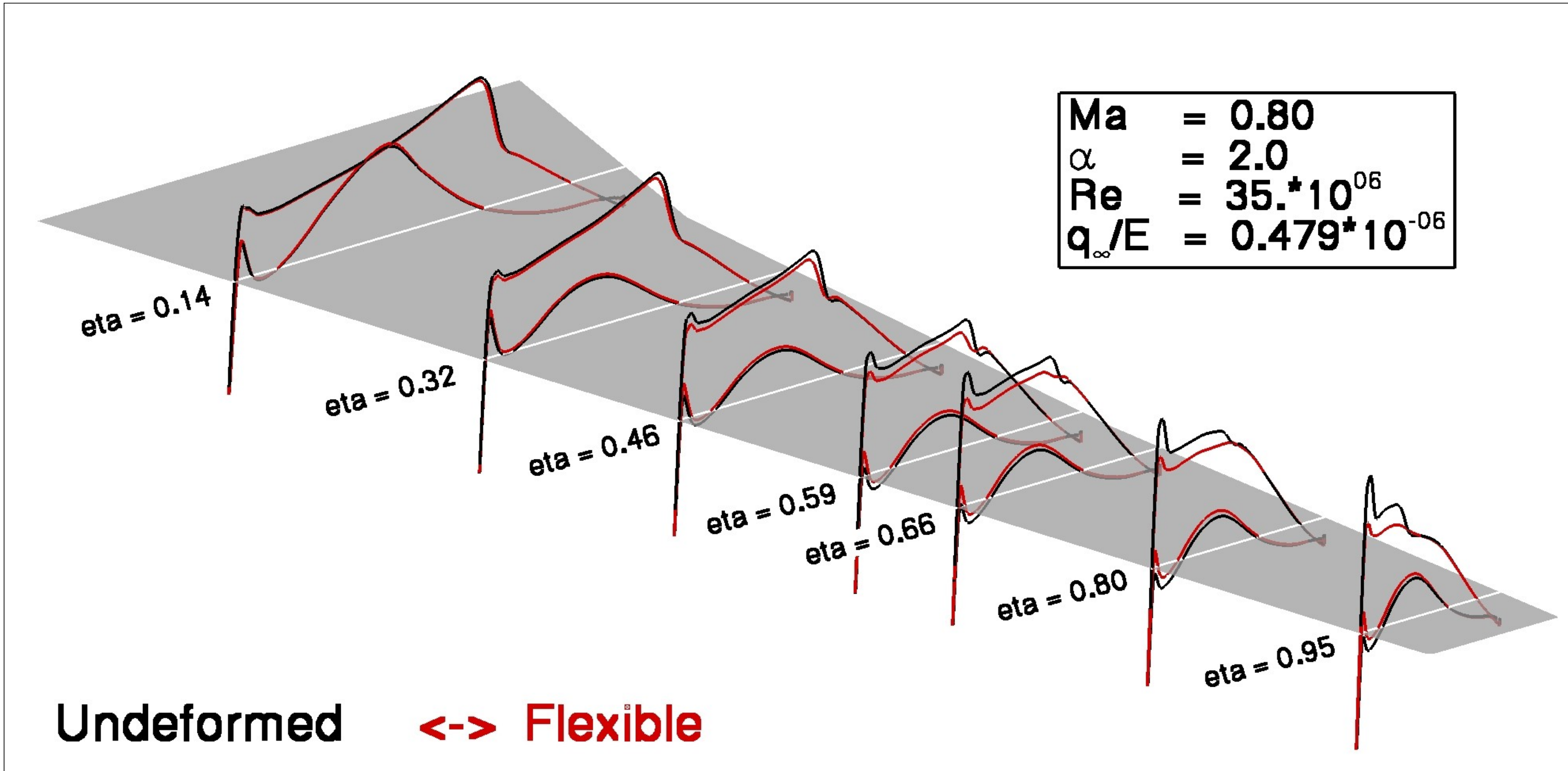
HIRENASD: Preliminary Aeroelastic Result for Wing Design



Numerical model: FLOWer, Navier-Stokes, EULER-symmetry B.C. in the wing root plane

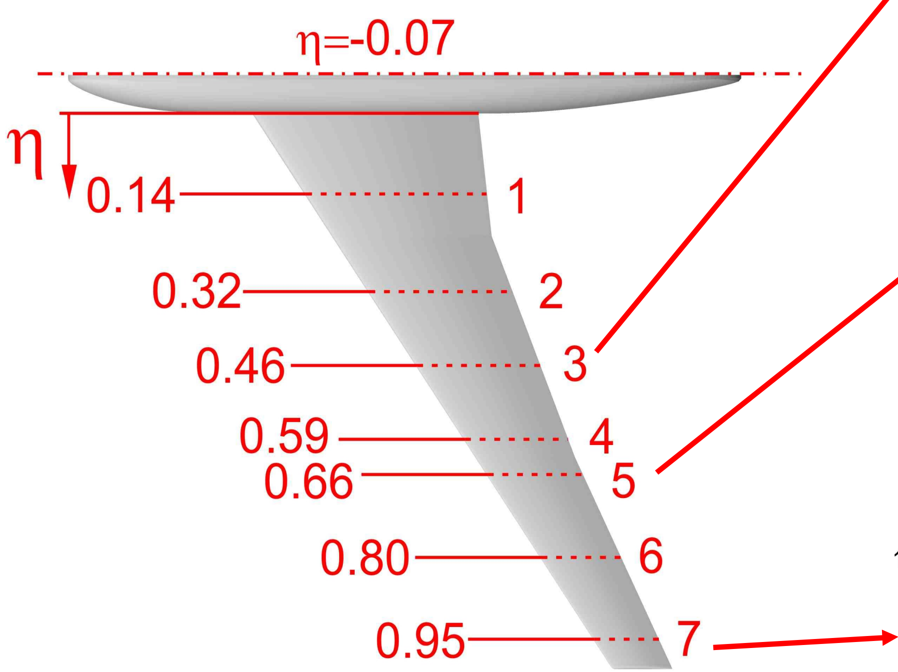
Comparison of predicted pressure distributions in the 7 spanwise measuring sections, black: Ignoring deformation, red: Aeroelastic equilibrium

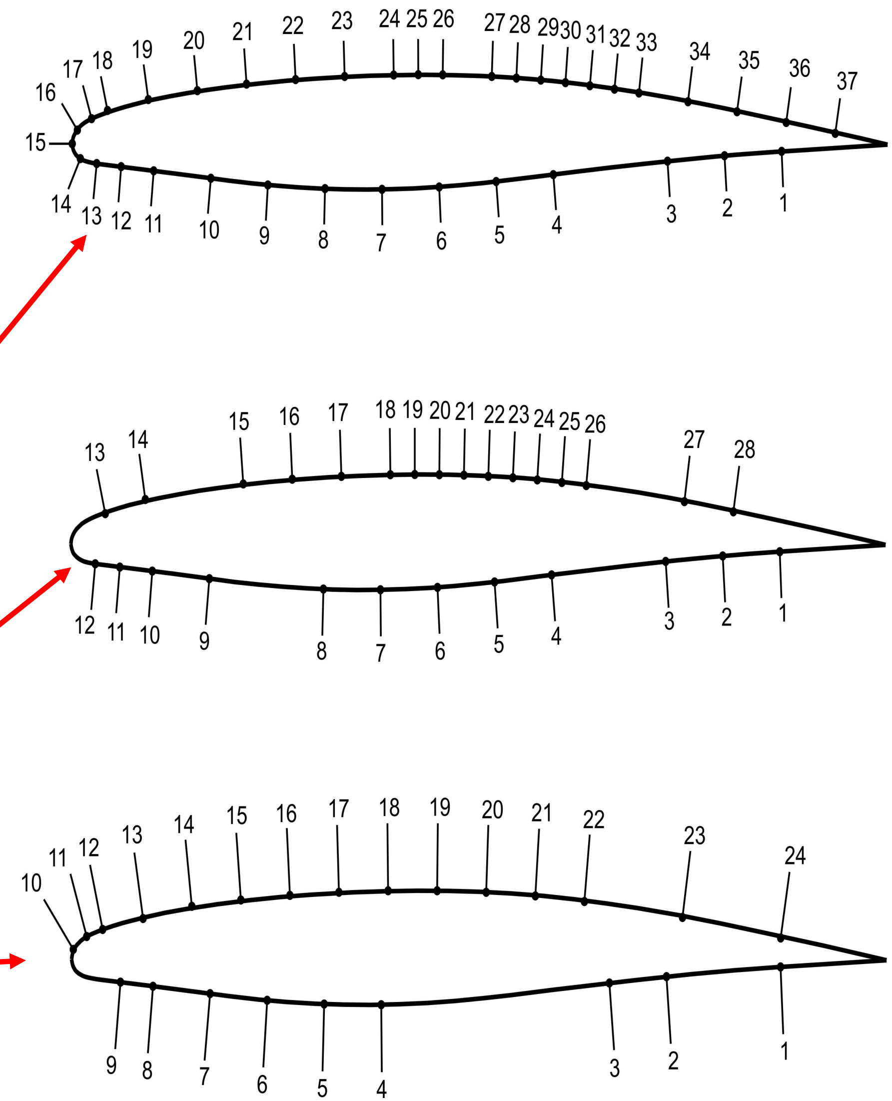
Wing root clamped at wind tunnel wall, i. e. no fuselage substitute present

Measuring Equipment for Pressure Distribution

Pressure Sensors:

259 *Kulite* in-situ pressure sensors
are integrated in wing,
distributed in 7 spanwise sections
→ detailed high speed measurement of transient pressure field feasible





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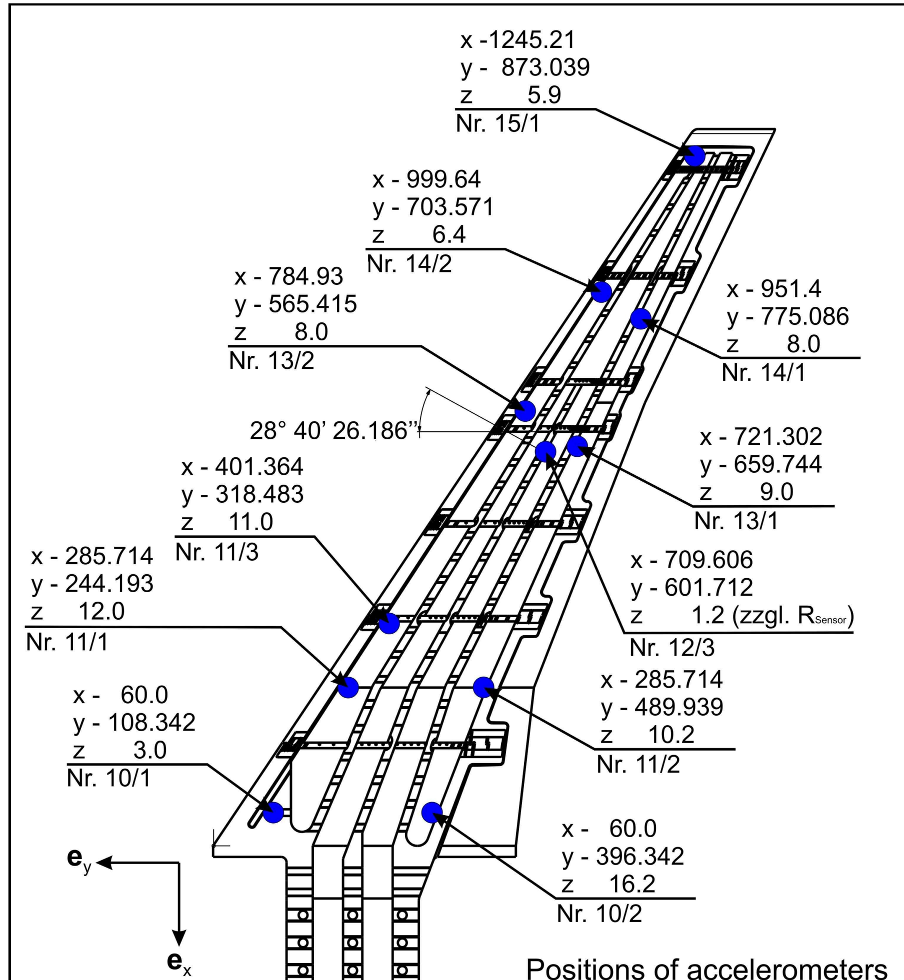
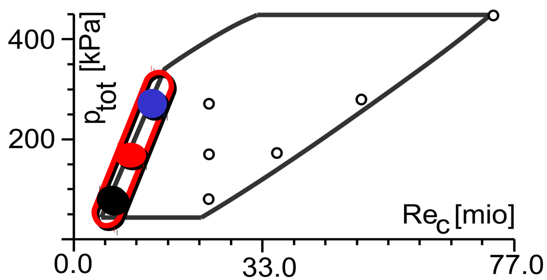
Stereo Pattern Tracking (SPT) and Accelerometers

48 markers on the pressure side of wing model for SPT, spacial accuracy 0.1 mm

Positions of accelerometers In the upper (suction side) part of wing model

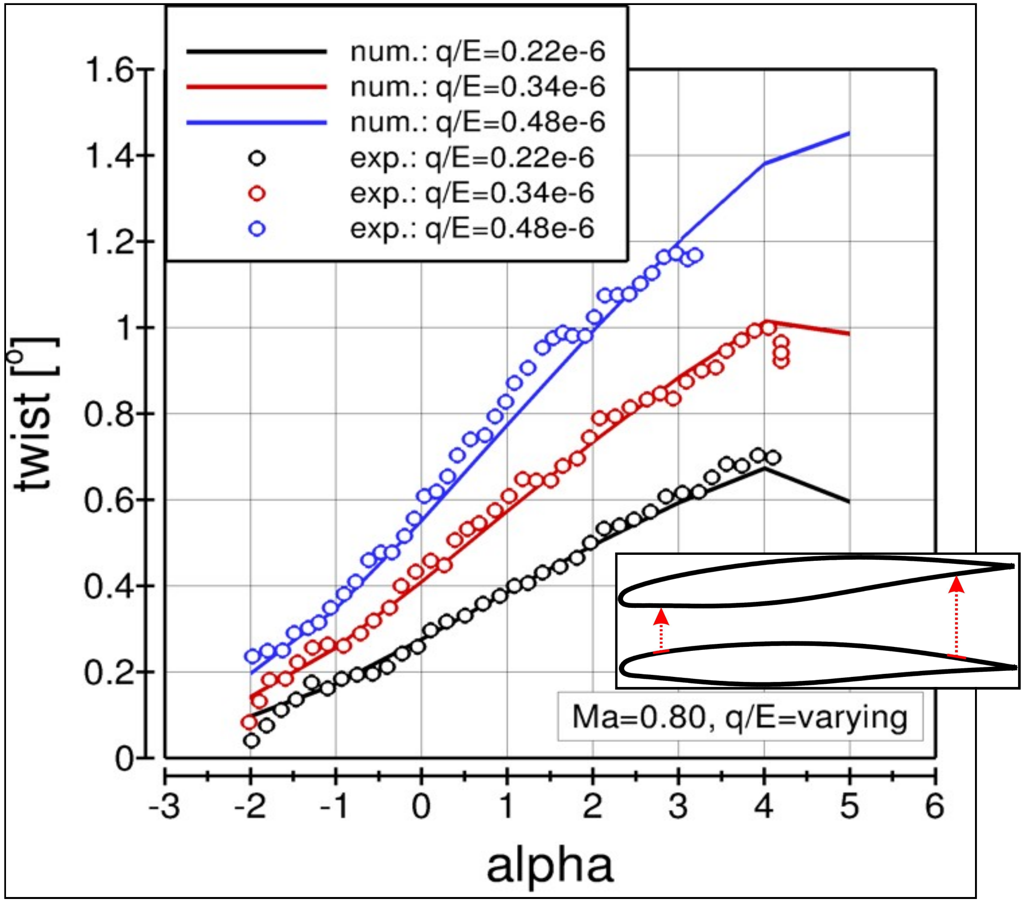


Exemplary Result of SPT Measurement and Prediction



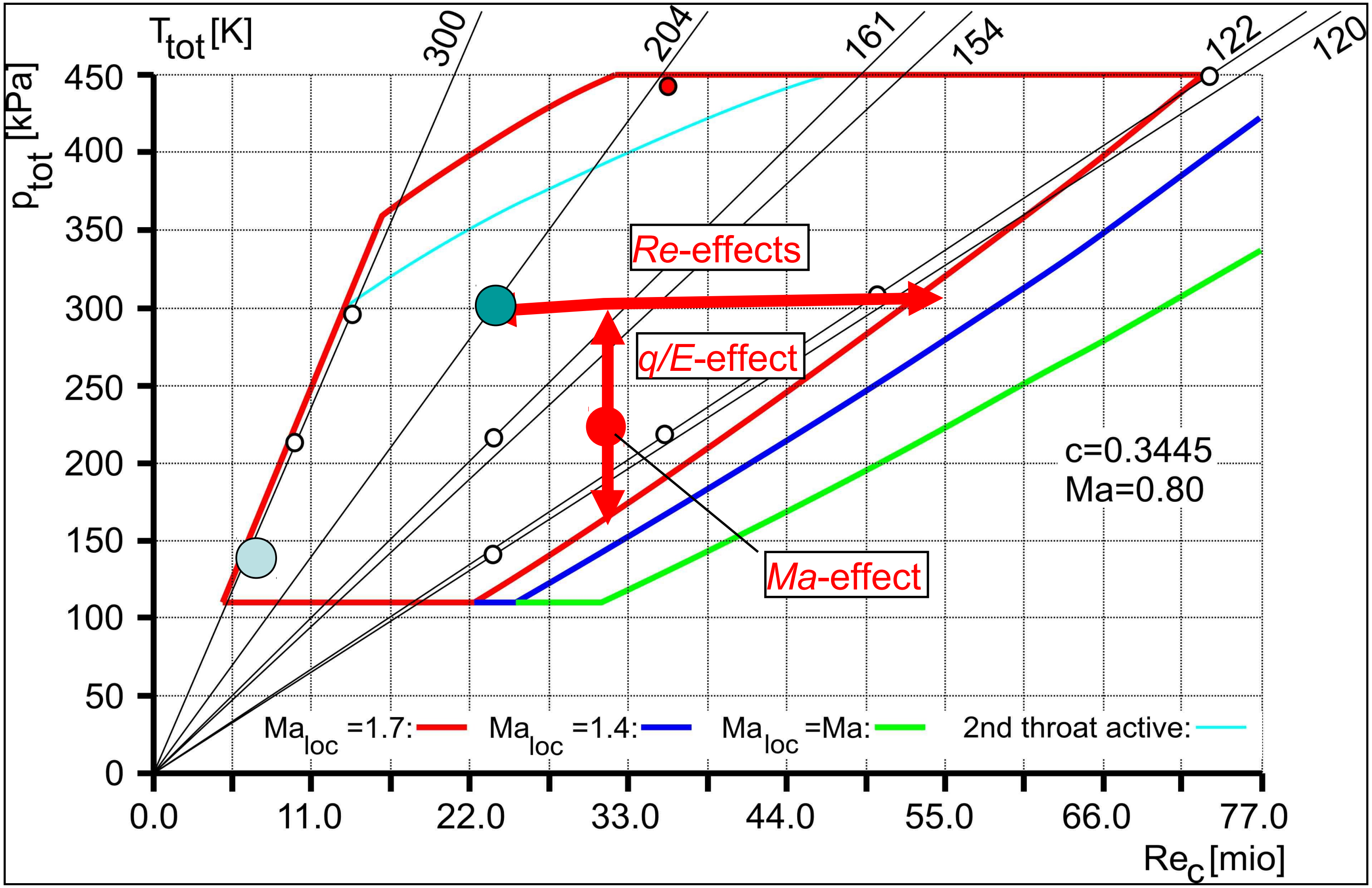
***q/E*-Variation** (small Re variation, fixed transition):
Influence of **q/E** on **aerodynamic twist at wing tip**

Mounted model assembly with markers for high speed *Stereo Pattern Tracking (SPT)*



HIRENASD Test Program and Conduction of Tests

Envelope of test conditions: Separate variation of *Ma*, *Re*, and *q/E*

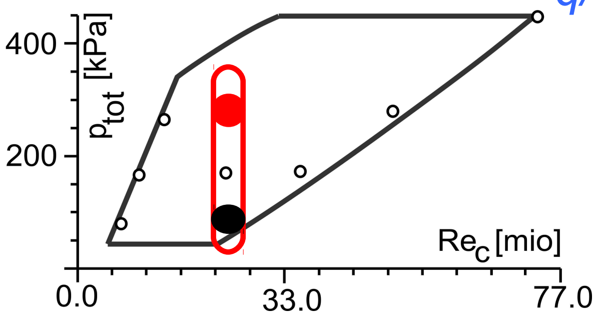


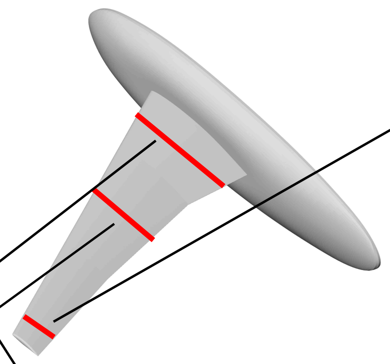
Workshop Test Cases at Re=7 and 23.5 10^6

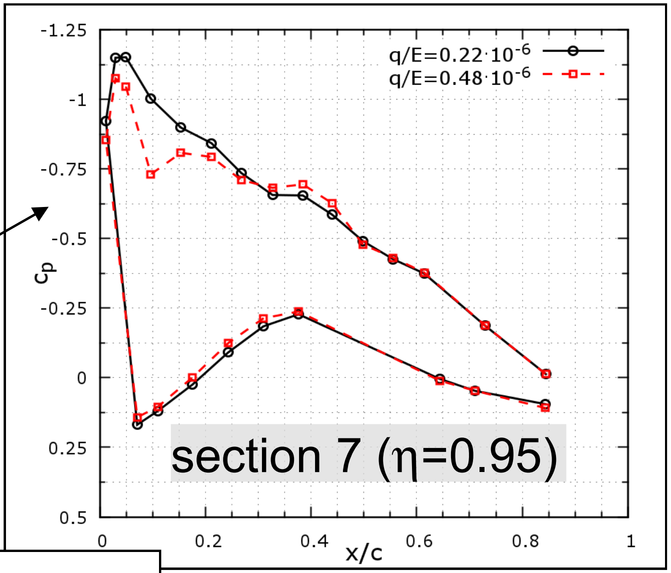
HIRENASD Static Wind Tunnel Tests

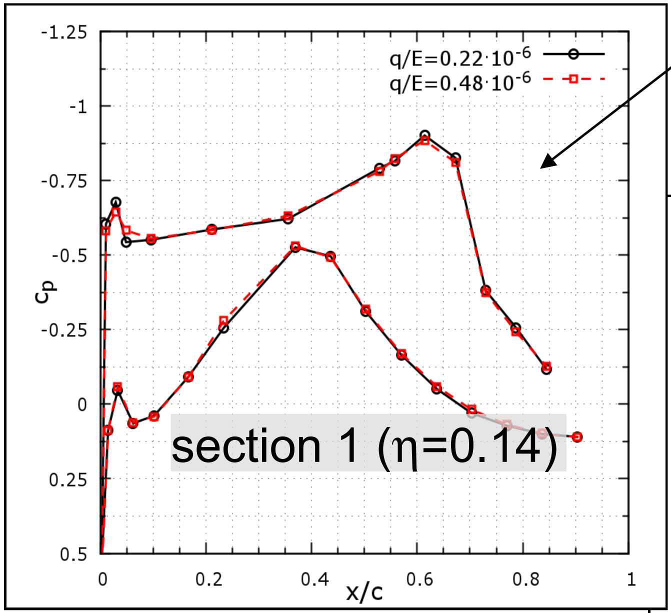
***q/E*-Variation:** Influence on pressure distribution

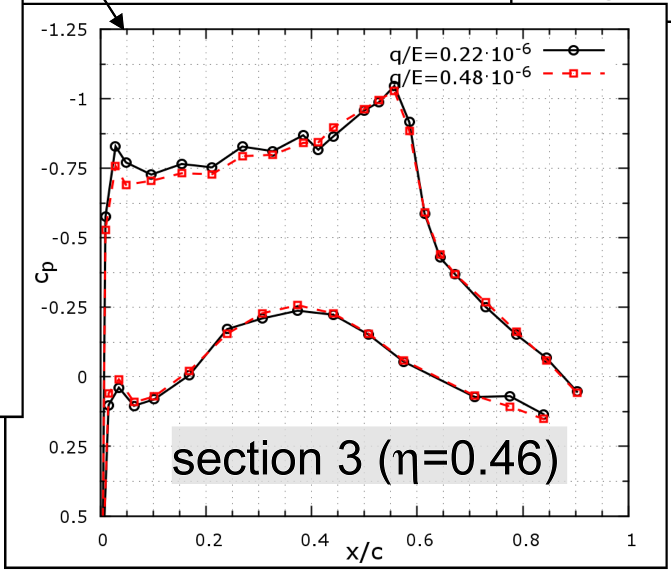
q/E = 0.22 ·10^{-6} , 0.48 ·10^{-6}











q/E=0.48e-6

q/E=0.22e-6

Ma=0.80

Re=23.5 mio.

alpha=3.0°

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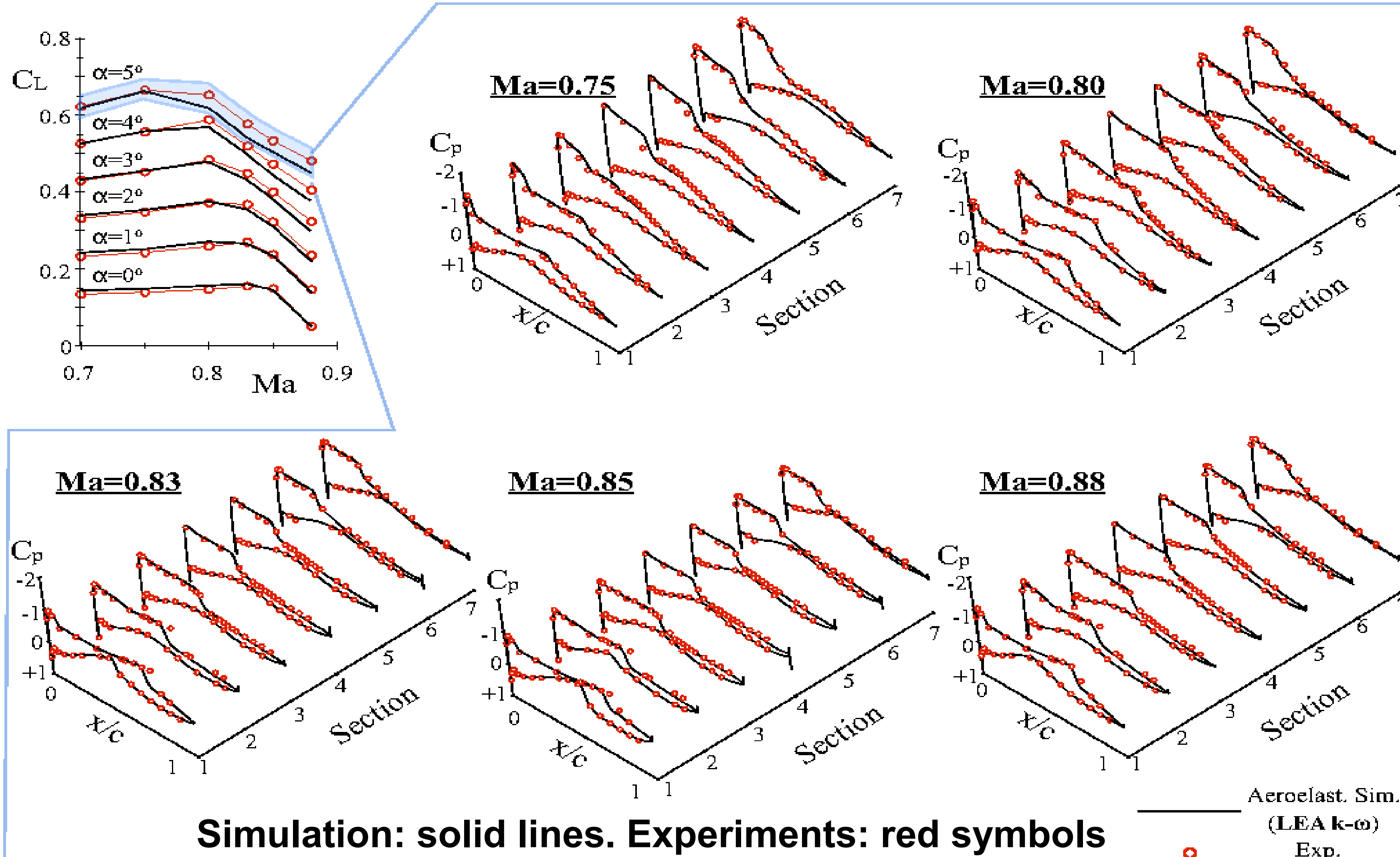
Validation: Influence of Ma on Cp & C_L Distribution in 7 Sections

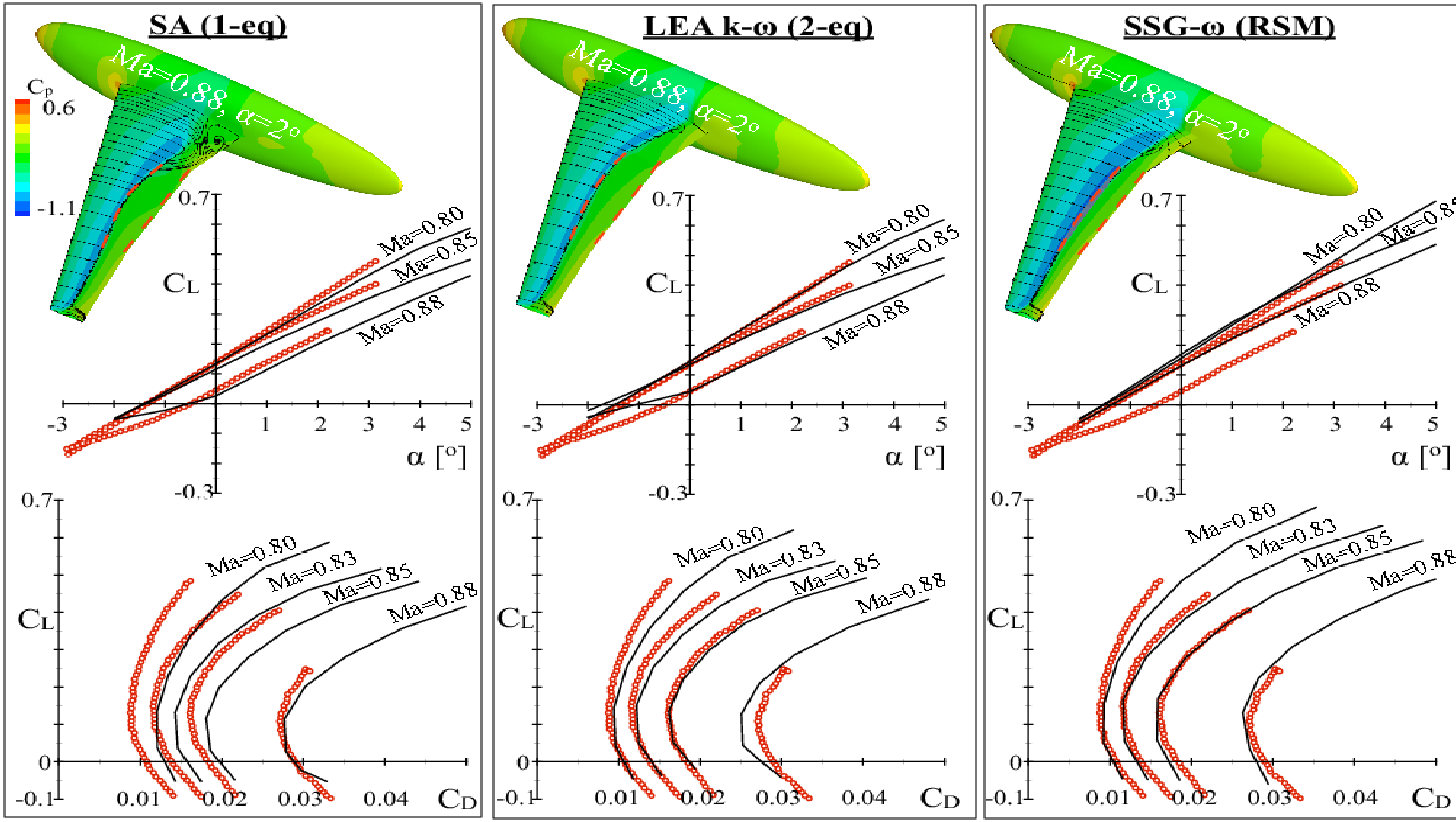
q/E = $0.48 \cdot 10^{-6}$, Re = $23.5 \cdot 10^{6}$, Ma varied: **Computational vs. Experimental Results**



Simulation: solid lines. Experiments: red symbols

Validation: Influence of Ma & Turbulence Model on C_L & C_D Polar

$q/E = 0.48 \cdot 10^{-6}$, $Re = 23.5 \cdot 10^{6}$, Ma varied: **Computational vs. Experimental Results**

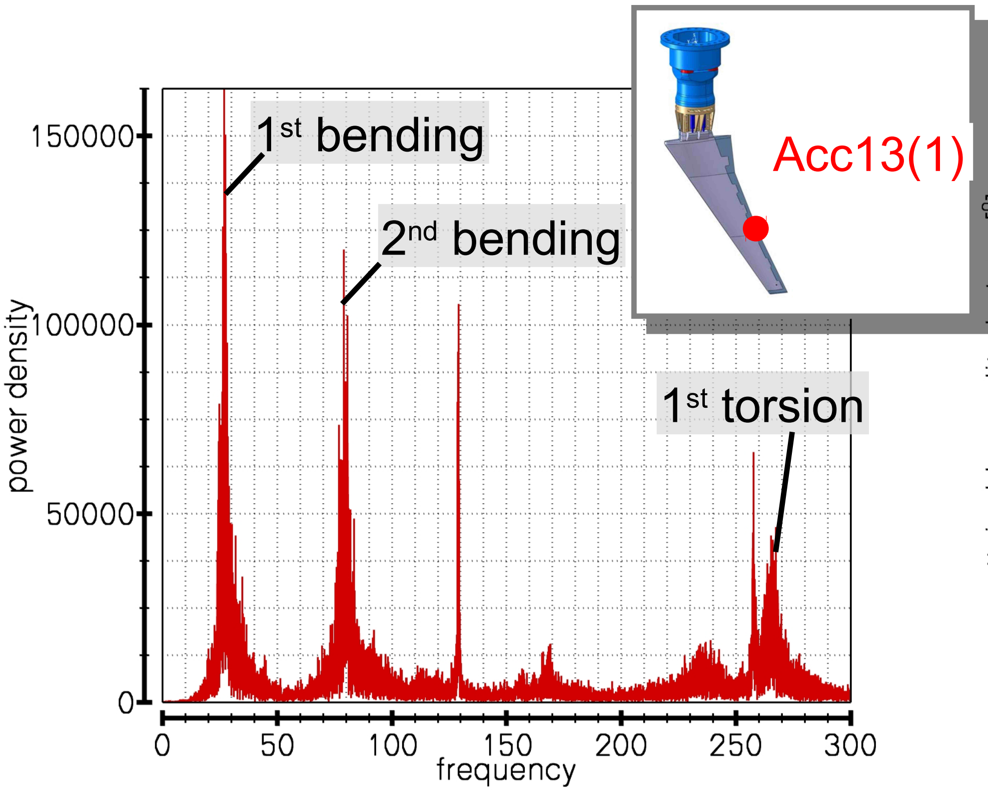


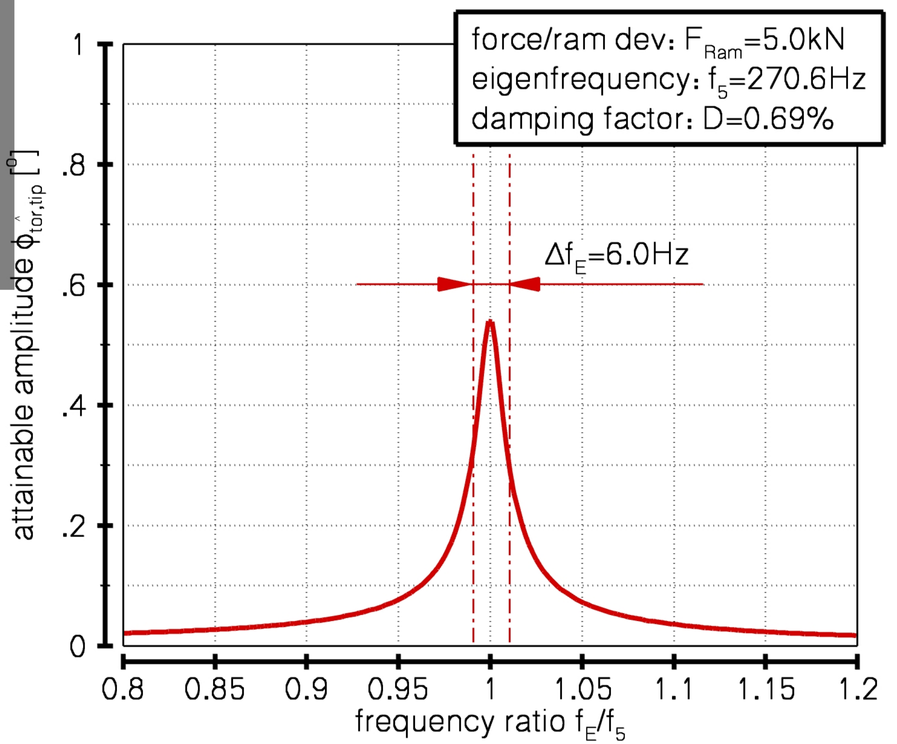
Simulation: solid lines. Experiments: red symbols

Stochastic Excitation: Frequencies from Static Tests

Determination of resonance frequency:

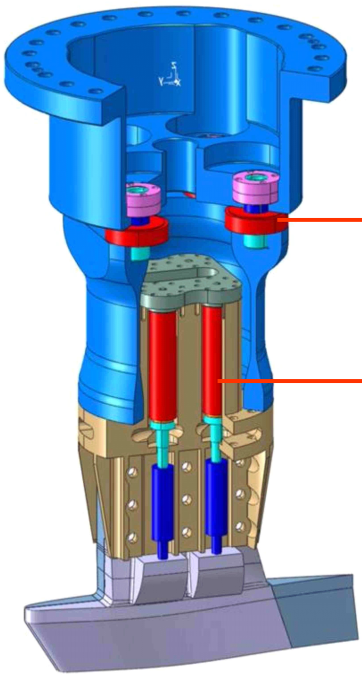
- Maximum effectiveness of excitation mechanism at resonance frequency
- Resonance frequency depending on flow conditions
- Determination of frequencies during steady wind tunnel tests from power spectra
- Accurate determination necessary due to low aerodynamic damping of higher modes

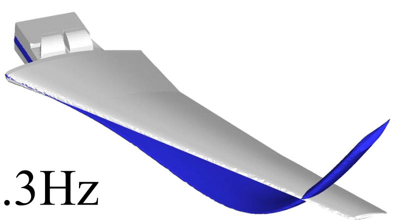




Band Filtering Process by Fourier Analysis of Dynamic Measurement Data, e. g. for HIRENASD Exp. 346

$Ma=0.85$, $Re=23.5\cdot10^{6}$, $q/E=0.22\cdot10^{-6}$

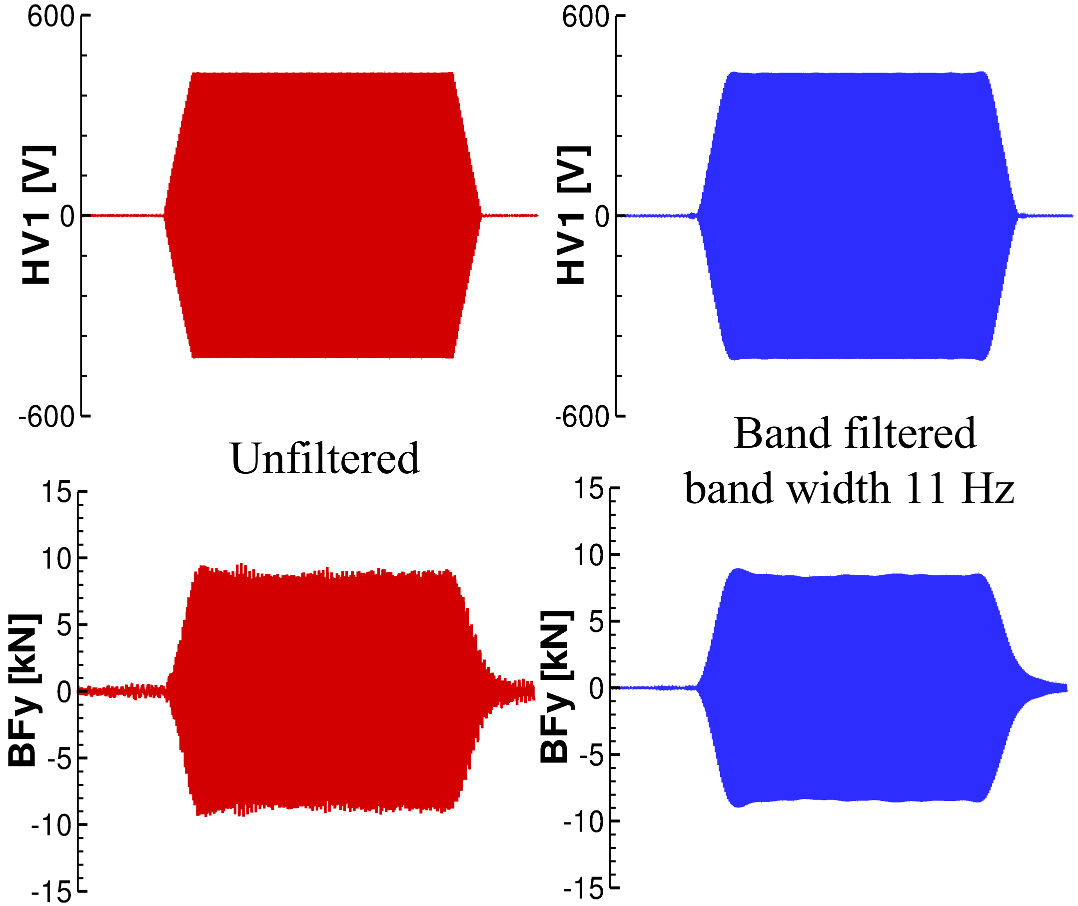




$f_A = 83.3\text{Hz}$

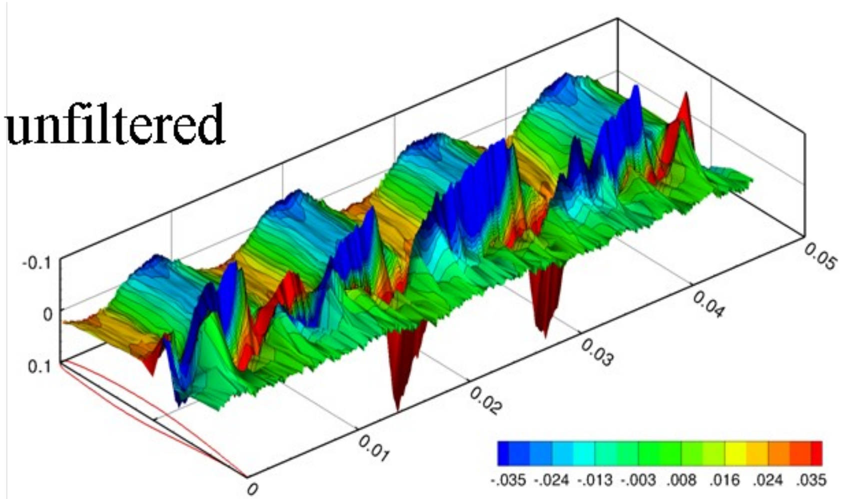
2. Bending dominated mode shape

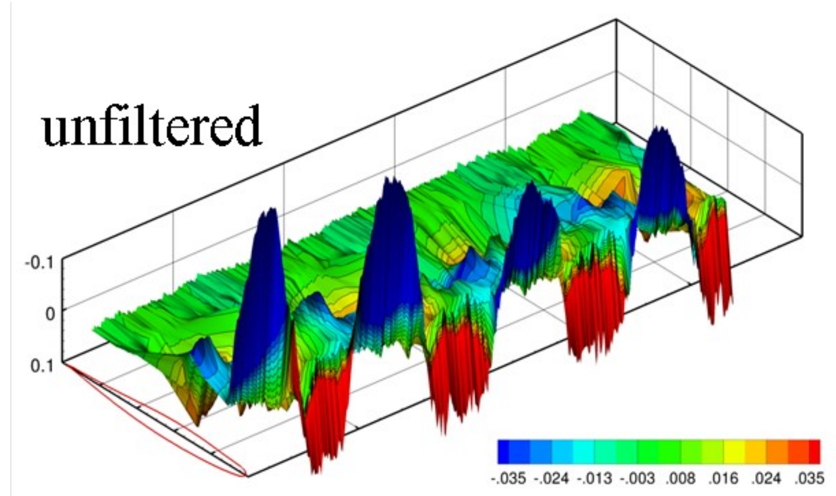
Control voltage of excitation piezo stacks



Balance force component normal to wing plane

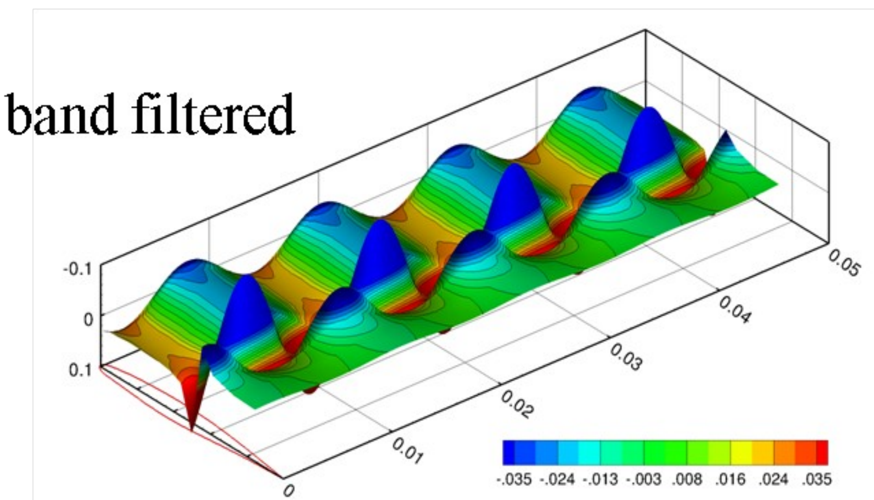
Band Filtering Process by Fourier Analysis of Dynamic Measurement Data, e. g. for HIRENASD Exp. 346

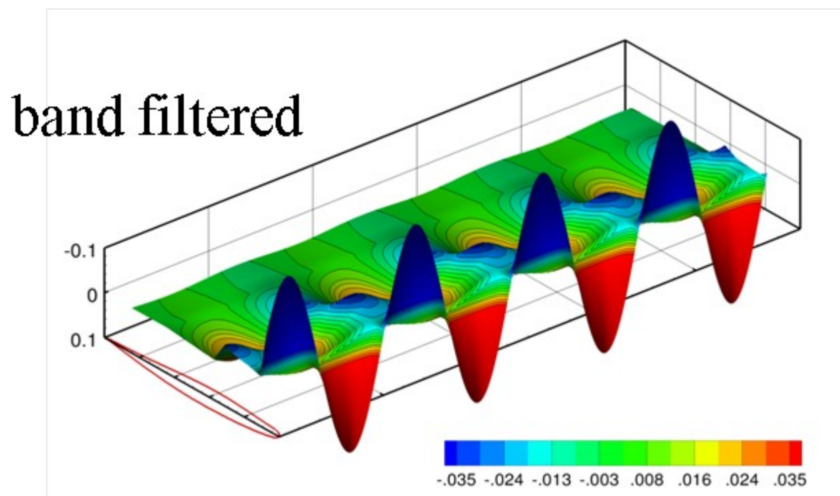




Top side

Bottom side

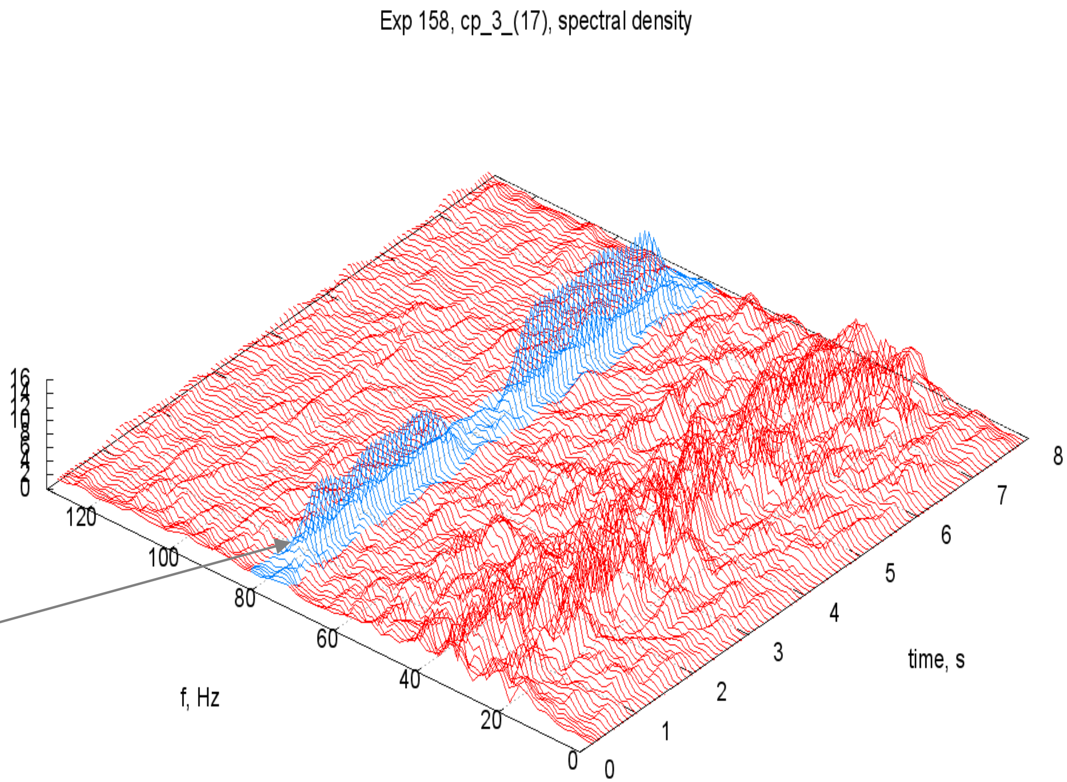




Band Filtering Process by Fourier Analysis of Dynamic Measurement Data, e. g. for HIRENASD Exp. 158

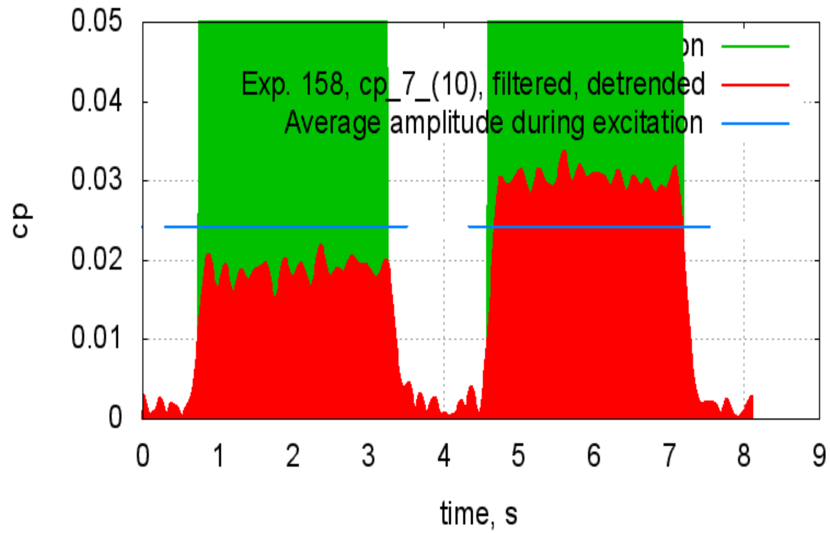
- Band-filtering around excitation frequency
- Band needs to be sufficiently wide – here 11Hz for 2nd bending mode (Exp. 158, pressure probe cp_3 (17)).

Ma	= 0.8
Re	= $7 \cdot 10^6$
q/E	= $0.22 \cdot 10^{-6}$
α	= -1.34°

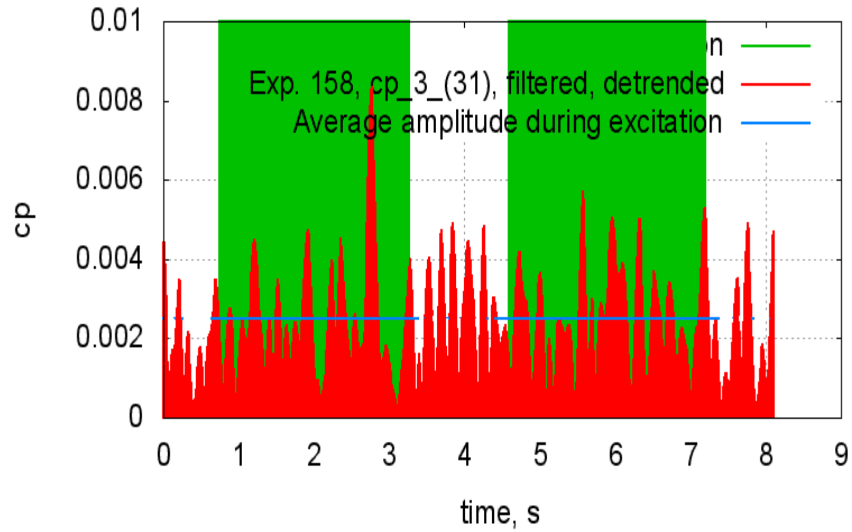


Blue band shows pressure variation clearly as response to excitation

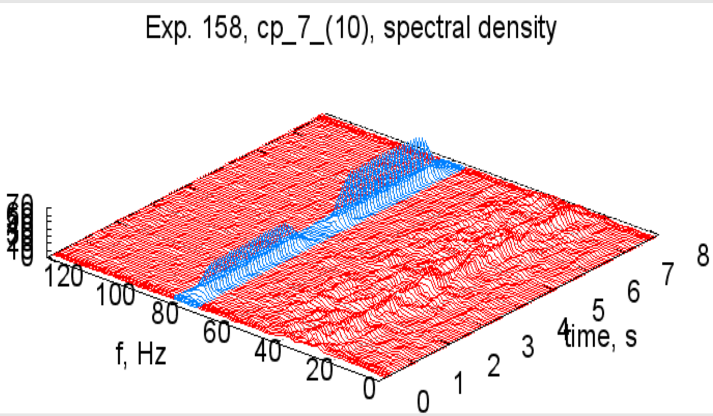
Band Filtering Process, e. g. for HIRENASD Exp. 158
Uncertainties of measured system response to excitation

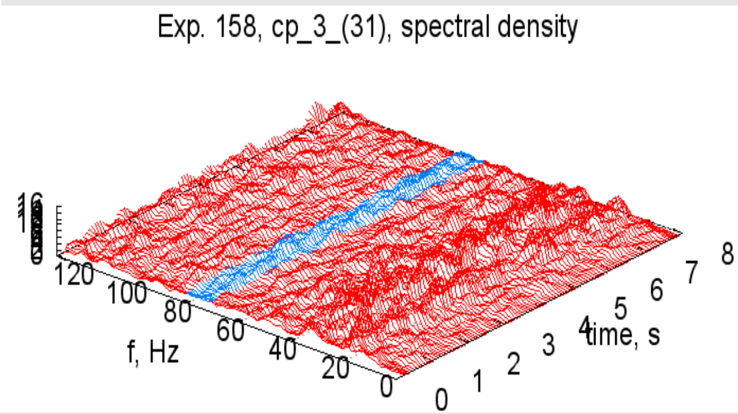


cp_7 (10): SPR value 7.97



cp_3 (31): SPR value 1.07





Simplified Signal-to-Perturbation-ratio:
mean amplitude 'excitation-on' / mean amplitude 'excitation-off'. Value >= ~1.

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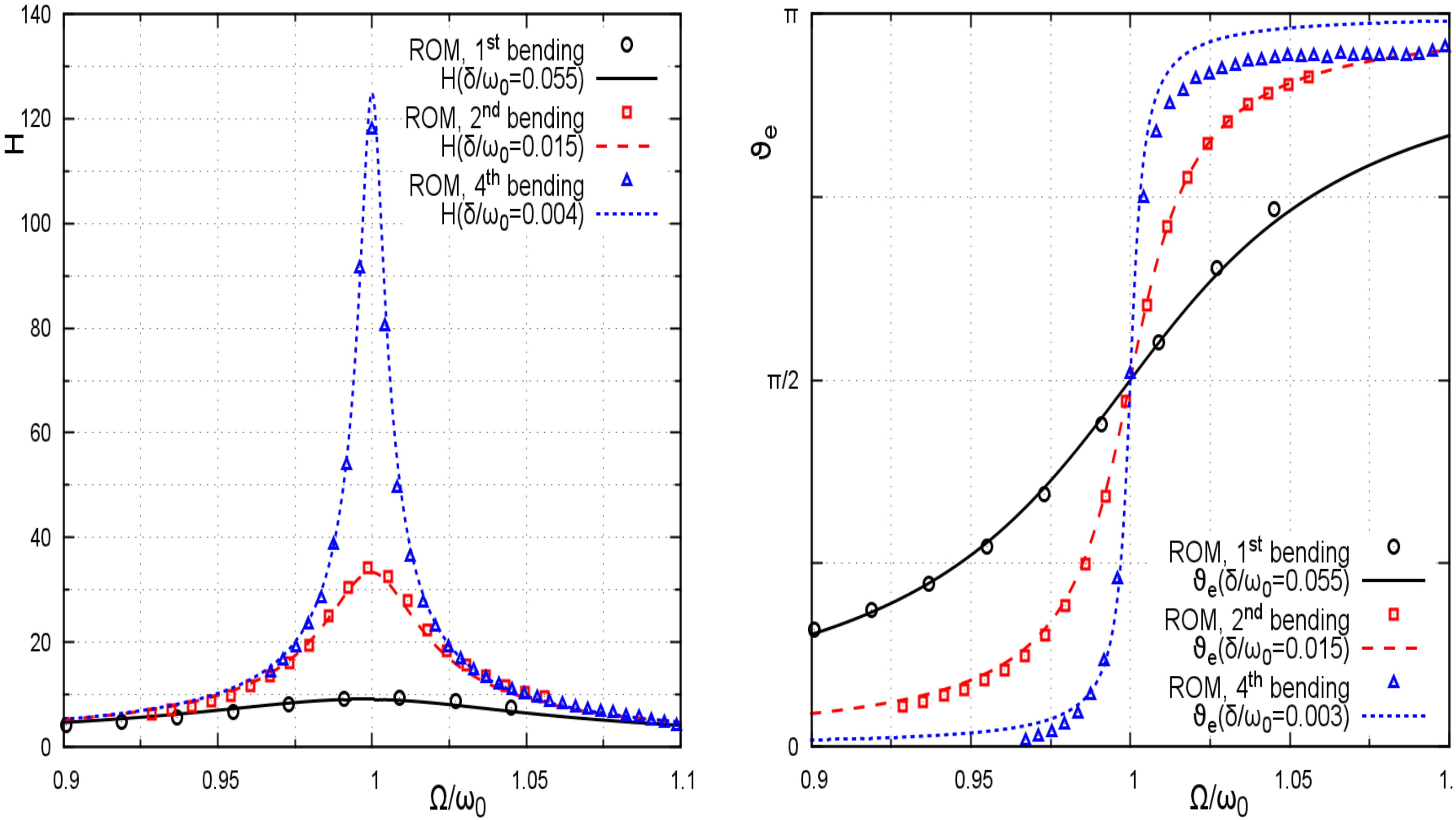
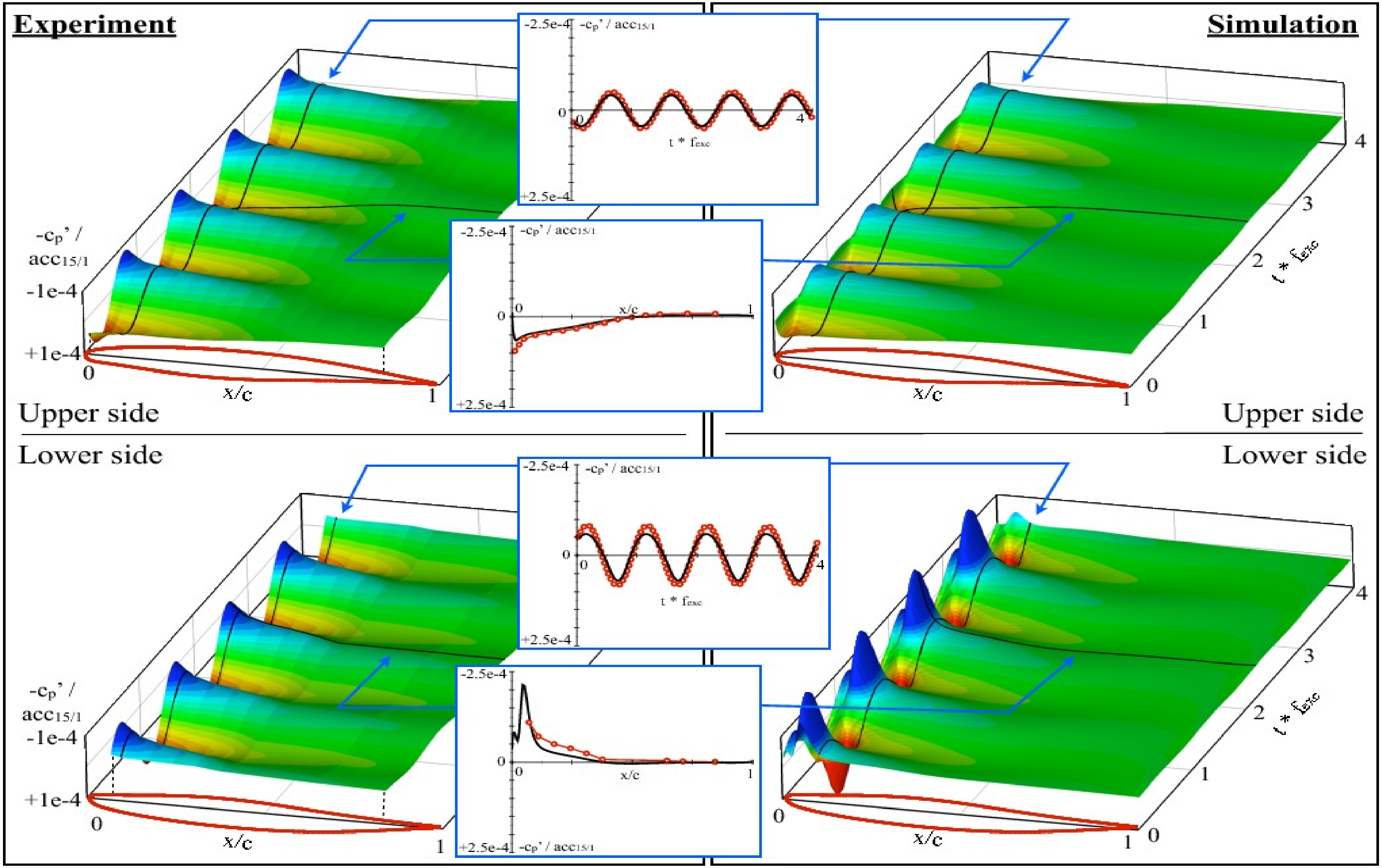
Excited Vibration Using Volterra-Wiener ROM (See Literature, e.g. W.A. Silva)

Amplification and Damping Characteristics Computed using Reduced Order Model



Validation: Cp’ in Section 7 During Exc. of *2nd* Mode, Exp. 271



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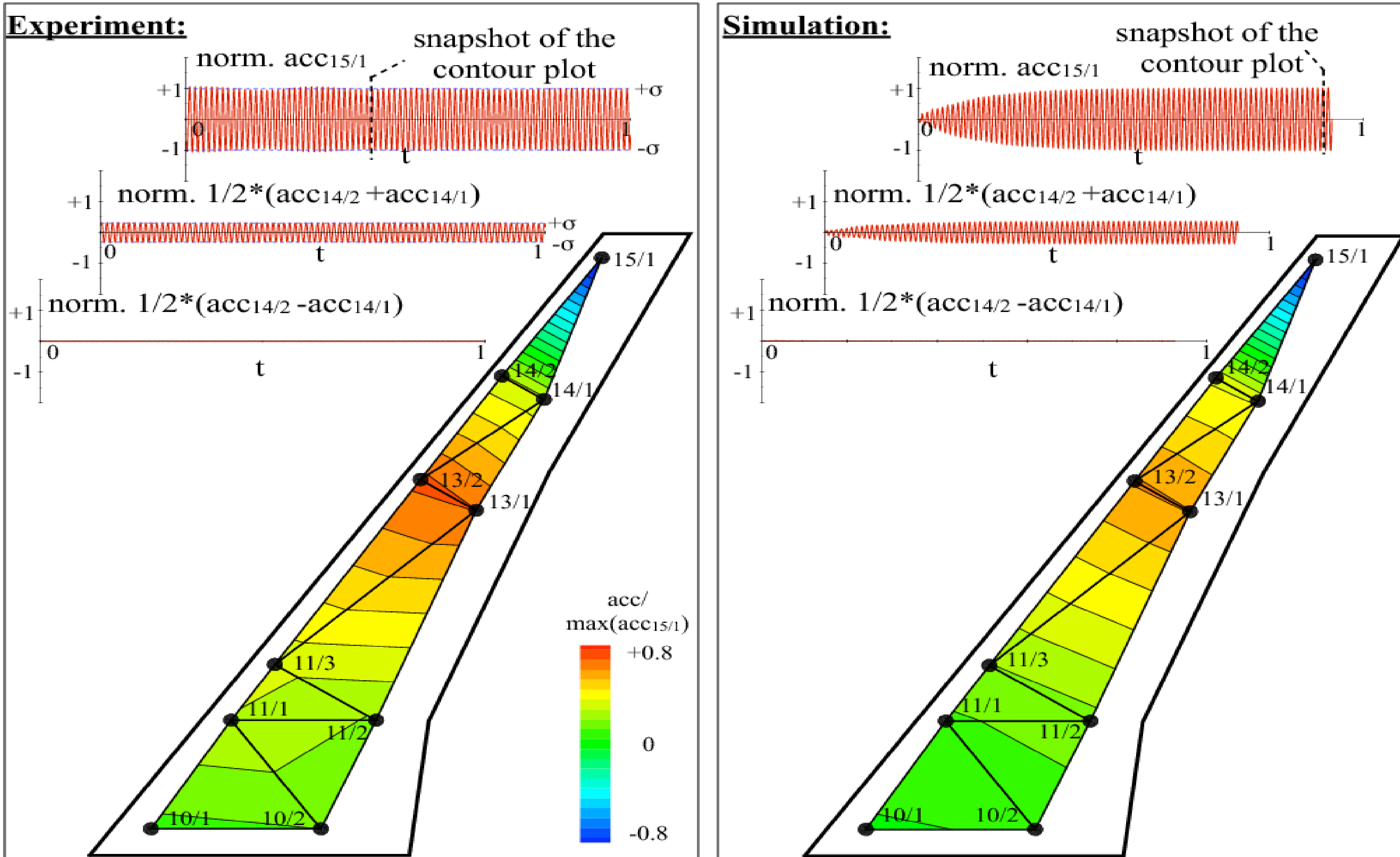
Validation: Accelerations During Exc. of 2nd Mode, Exp. 271



Conclusions

- HIRENASD model very stiff, but nevertheless, the experiments provide aero-elastic data over a wide range of parameters q/E, Ma, Re
- Stationary polars (at least nominally) have been performed as well as dynamic polars with defined vibration excitation by applying internal force couples at wing root
- Stochastic flow perturbations during stationary polars enabled via accelerometers the finding of natural mode shapes and frequencies
- Because of the high stiffness of the model, defined vibration excitation frequencies chosen close to natural frequencies to achieve measurable amplitudes
- 1st natural mode excitation strongly affected by the stochastic perturbations, 2nd and 3rd mode excitation less perturbed resulting in higher signal to perturbation ratio
- Band filtering of dynamic data and formulations in the sense of transfer function analysis provide data useful for dynamic code validation
- Moving averaging of balance forces in stationary polars yielded good results for lift and drag, except for some conditions where no stationary flow was established which are not discussed in this workshop. (Upstream propagating shock waves as phenomena partly similar to shock buffet, but without significant flow separation)

Thank you for
your attention!

HIRENASD Elastic Model Assembly for Code Validation