Aeroelastic Prediction Workshop

Overview & Lessons Learned from the Aeroelastic Prediction Workshop

Jennifer Heeg, Pawel Chwalowski, David Schuster, Mats Dalenbring, Adam Jirasek, Paul Taylor, Dimitri Mavriplis, Alexander Boucke, Josef Ballmann and Marilyn Smith

AePW Website: https://c3.nasa.gov/dashlink/projects/47/

Advances in Nonlinear Unsteady Aerodynamic Flows Symposium
US National Congress of Computational Mechanics
Raleigh, NC , July 22-25

Outline

- Workshop overview
- Overview of lessons learned
- Lessons learned in separated flow simulation & experiments
- Path forward discussion

Outline

- **Workshop overview**
  - **Groundwork**
  - **Configuration discussion**
- Overview of lessons learned
- Lessons learned in separated flow simulation & experiments
- Path forward discussion

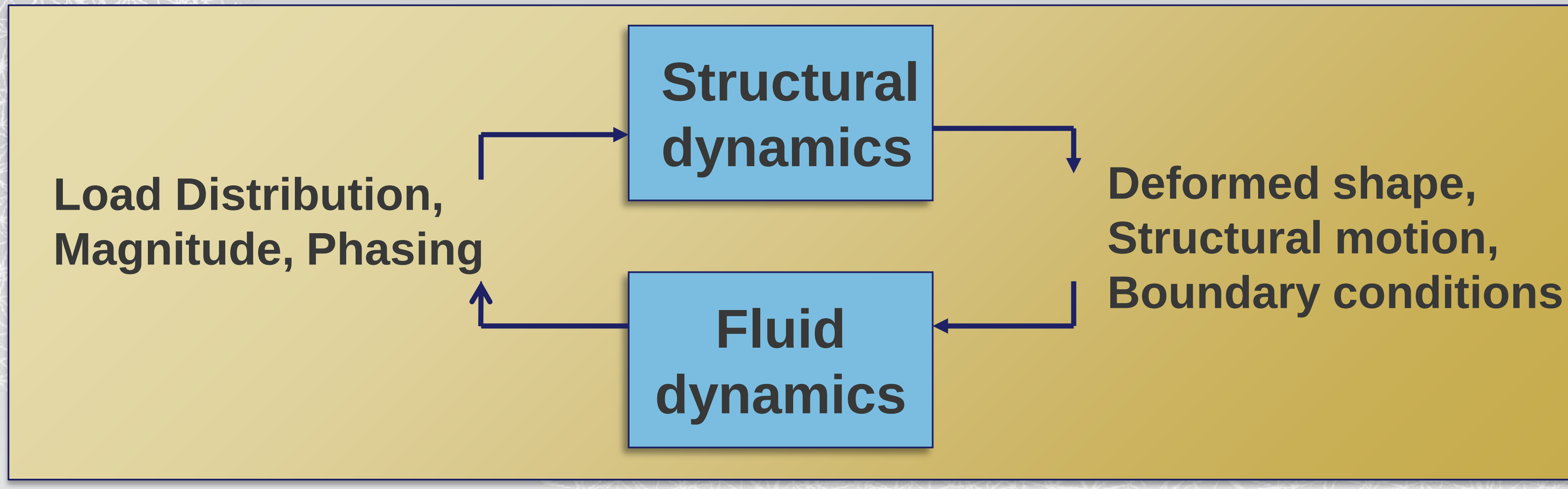
Aeroelastic Computational Benchmarking

- **Technical Challenge:**

  Assess state-of-the-art methods & tools for the prediction and assessment of aeroelastic phenomena

- **Fundamental hindrances to this challenge**
  - No comprehensive aeroelastic benchmarking validation standard exists
  - No sustained, successful effort to coordinate validation efforts
- **Approach**
  - Perform comparative computational studies on selected test cases
  - Identify errors & uncertainties in computational aeroelastic methods
  - Identify gaps in existing aeroelastic databases
  - Provide roadmap of path forward

Building block approach to benchmarking & validation



Validation Objective of 1st Workshop

Unsteady aerodynamic pressures due to forced sinusoidal oscillations

Future Workshops

- Directed by results of this workshop
- Directed by big-picture assessment of needs & interests

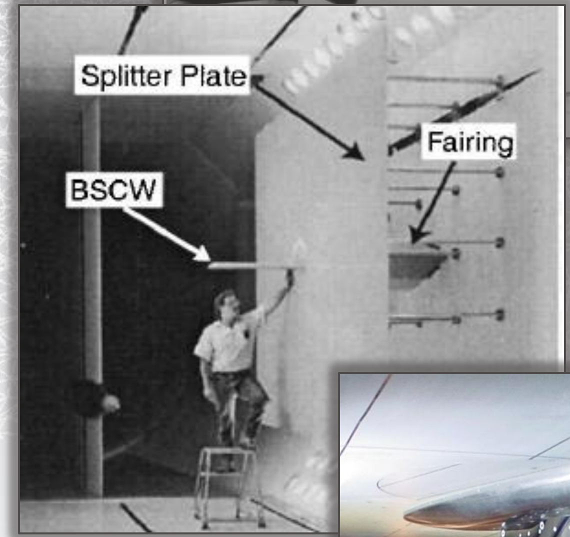
Aeroelastic Prediction Workshop

- Workshop presentations are on AePW website
  https://c3.nasa.gov/dashlink/projects/47/

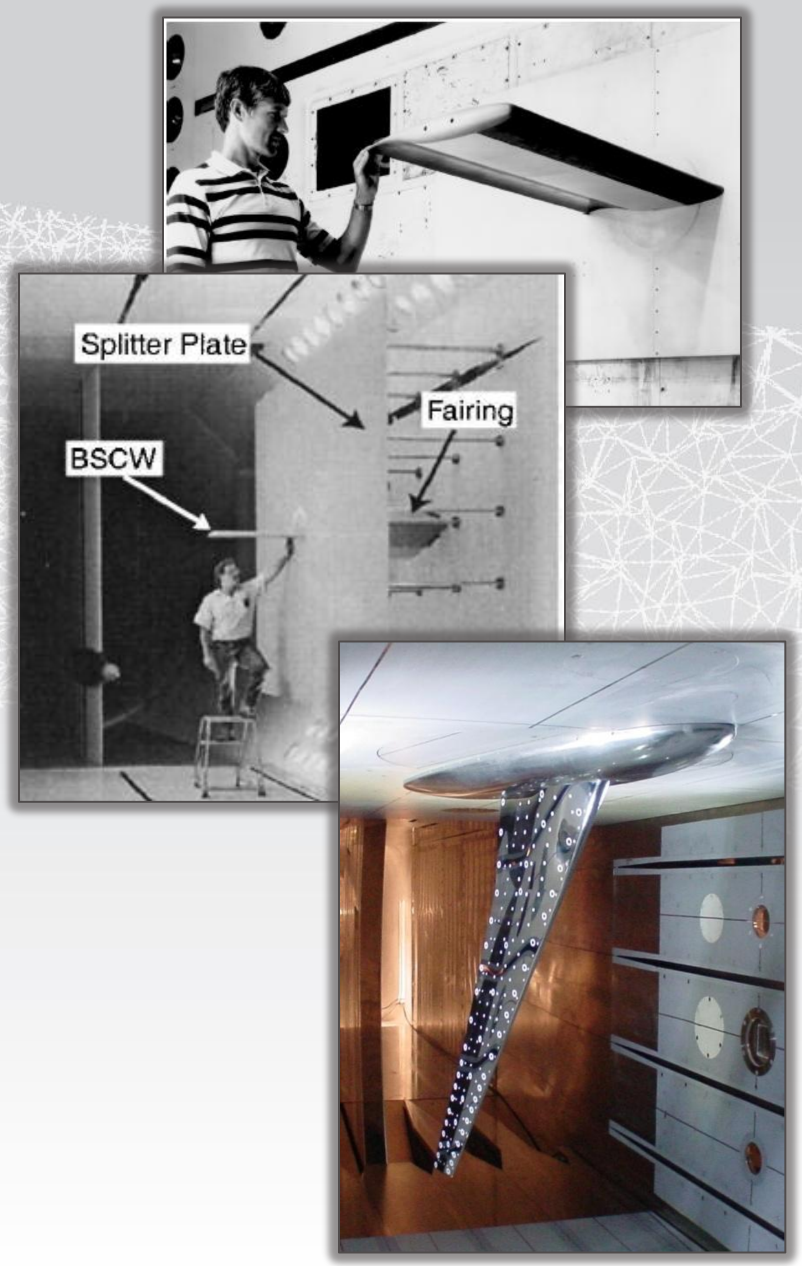
- Reported results in special sessions at ASM, SDM & IFASD

Configurations Selected

- Rectangular Supercritical Wing (RSW)
- Benchmark Supercritical Wing (BSCW)
- High Reynolds number Aero-Structural Dynamics Model (HIRENASD)



Configuration / Data Set Selection Rationale



- Perceived Simplicity & Complexity
  - Geometric
  - Flow Physics

- All configurations have
  - Transonic flow
  - Unsteady pressure data
  - Forced transition to turbulent flow
  - Steady data
  - Forced oscillation data

- Availability
  - Distribution unrestricted

Configuration / Data Set Selection Compromises

- Configurations are not "aeroelasticky"
- Deflection data is sparse
- Expected flow phenomena does not encompass all possible applicable flows for aeroelastic configurations
- Results from workshop comparisons can not be directly translated to critical aeroelastic quantities
- Results of this workshop will only tell us how well we can predict the class of phenomena that we are looking at:
  - Forced transition
  - Shock-separated flow
  - Forced oscillations
  - Uncoupled and weakly coupled aerodynamics

Outline

- Workshop overview
- **Overview of lessons learned**
- Lessons learned in separated flow simulation & experiments
- Path forward discussion

General questions addressed by lessons learned

- How good are our tools, and what aspects of those tools need further development?

- What comparison data or experimental data characteristics would have improved our confidence in experiment representing relevant truth?

Rectangular Supercritical Wing (RSW)

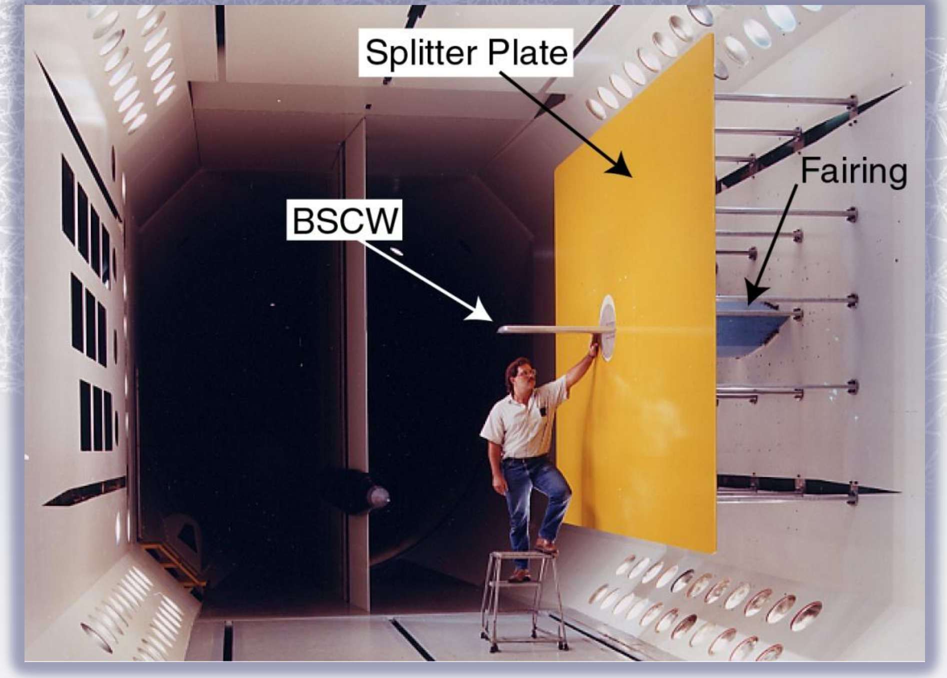
- Simple, rectangular wing
- Structure treated as rigid

- Lessons Learned:
  - Wall effects modeling

Benchmark Supercritical Wing (BSCW)

- Simple, rectangular wing
- Structure treated as rigid

- Lessons Learned
  - Separated flow modeling



HIRENASD

- 3-D aeroelastic wing with generic fuselage model
- Treated as aeroelastic here
  - Relatively weak aeroelastic coupling
- Forced oscillation at 2nd bending mode frequency

- Lessons learned
  - Importance of data processing influences
  - Quantifying variations
  - Criticality of static aeroelastic behavior for unsteady aerodynamics

- **What did we learn about test case selection?**
  - There were too many test cases in this workshop. The number of configurations- 3- diluted ... or the ... sing a ... added ... usly ... and ... tify ... able ... not

- **What have we learned regarding postprocessing of computational data?**
  - The amount of information generated in performing an unsteady CFD calculation is ...

- **What have we learned regarding experimental data?**
  - "Steady" is a misnomer, particularly in the case of experimental data, but also perhaps in ... ls ... ns ... ed

- **What have we learned regarding flow solvers?**
  - Flow solutions that offer better fidelity in capturing turbulence, such as LES or DES, have generally been recommended in the literature for analyzing cases "massively separated ... g upper ... of the ... e shock ... imity of ... ence of ... even fo ... esults a ... the sta ... BSC

- **What were the most challenging aspects regarding our chosen configurations? What were the consequences of these aspects?**

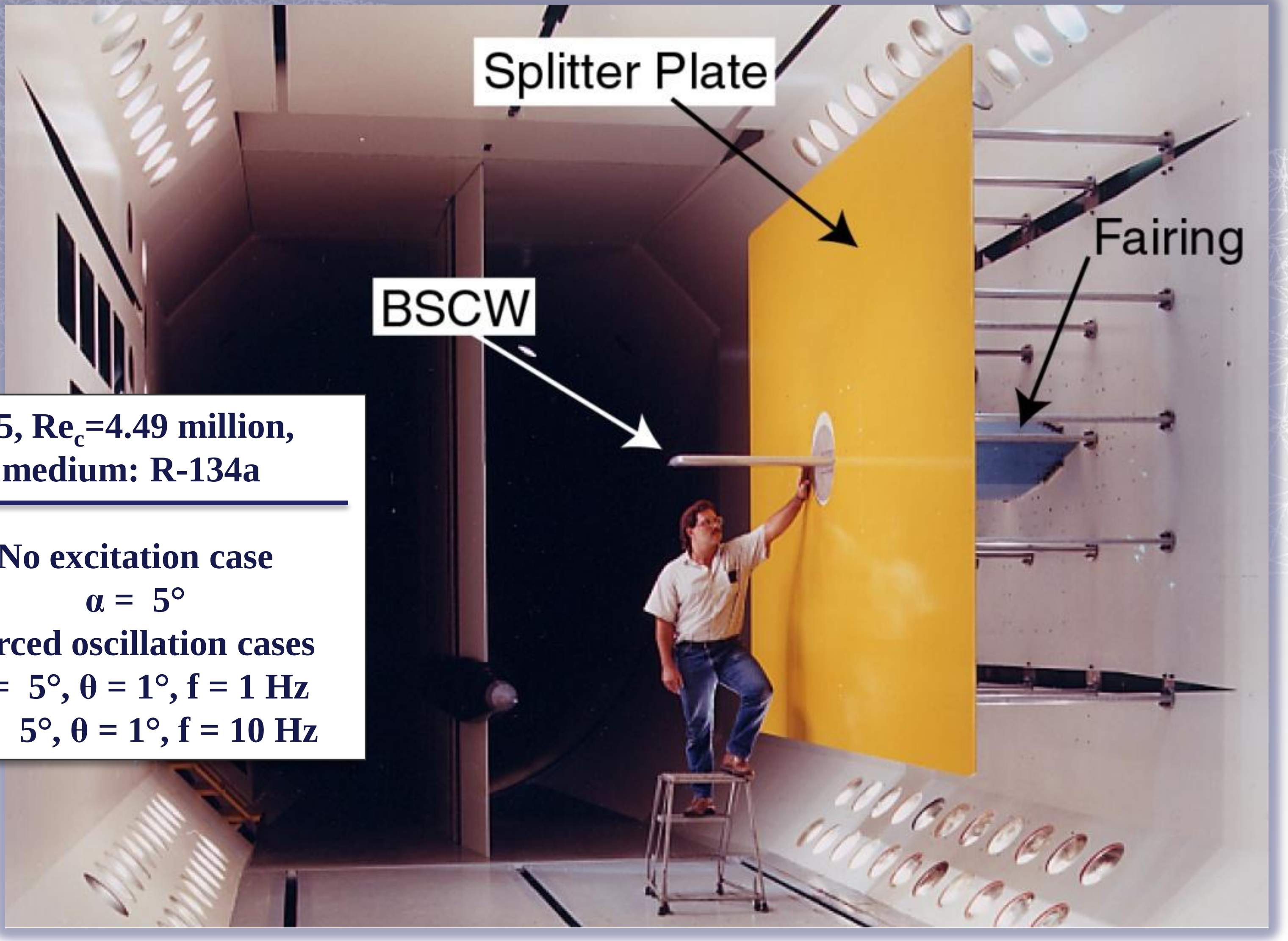
- **What have we learned about the state of the art in aeroelastic computations?**
  - Using RANS, we cannot accurately capture separated flow associated with the BSCW at the chosen test conditions. Although the test case was thought to contain moderately separated flow, the region of separation appears to extend from the mid-chord (shock location) to the wing trailing edge. Further, the ... flow are of essential interest in our studies. While RANS ... averaged influence of separation for small ... unforced or forced

Outline

- Workshop overview
- Overview of lessons learned
- **Lessons learned regarding separated flow experiments & modeling**
- Path forward discussion

- **What have we learned regarding flow solvers?**
  - **Reynolds-Averaged Navier-Stokes (RANS) with Spalart-Allmaras (SA) or Menter's SST turbulence modeling is the State of the Art (or rather state of the current practice in the CFD community)**
  - **The degree of separation previously thought to be "moderate" breaks the RANS solvers**.
  - Flow solutions that offer better fidelity in capturing turbulence, such as LES or DES, have generally been recommended in the literature for analyzing cases "massively separated flows" exist, usually occurring at high angles of attack. The highest mean angle of attack case for the AePW was the BSCW configuration, α = 5º. This test case generated what was assessed as moderately separated flow. The workshop results for BSCW led to the assessment that the URANS solutions were insufficient for this case. Some analysts are pursuing higher order CFD methods for this configuration. In this case, at a moderate angle of attack, the separated flow features are significant enough to cause a qualitative change to the shock motion and qualitative changes in the aft loading. While these changes may or may not be significant for integrated loads such as lift and pitching moment coefficient, they are likely significant for assessing aeroelastic stability, which is highly dependent on phase relationships and load distribution.
  - In order to get the steady pressure distribution correct, it is essential to get the stati aeroelastic deformed shape correct. Failure to do this results in effective changes in th ...le of attack. Using the rigid shape, rather than the deflected aeroelastic shape resulted ...ssure distribution.
  - ...illatory response are not standardized. Seve ...whether the difference

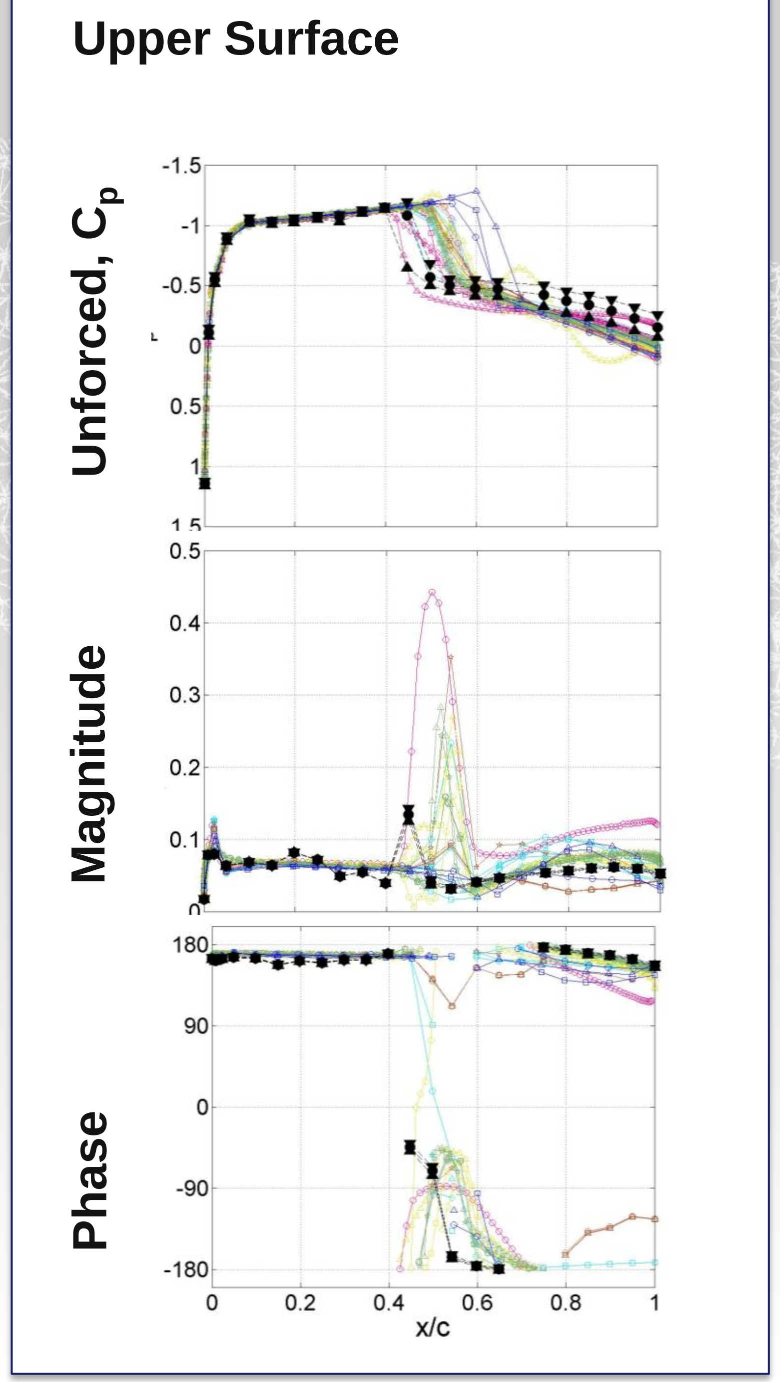
Benchmark Supercritical Wing (BSCW)

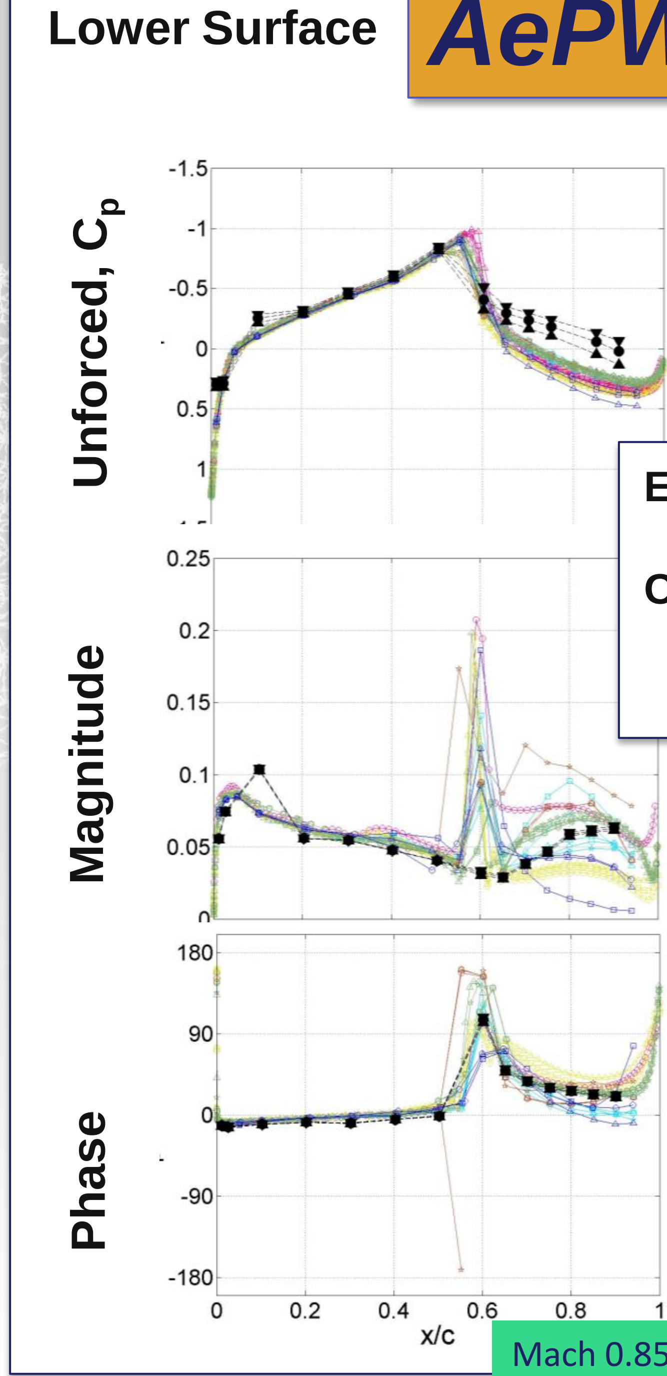


M=0.85, Re_c=4.49 million,
Test medium: R-134a

No excitation case
$\alpha = 5°$
Forced oscillation cases
$\alpha = 5°, \theta = 1°, f = 1$ Hz
$\alpha = 5°, \theta = 1°, f = 10$ Hz

AePW Results



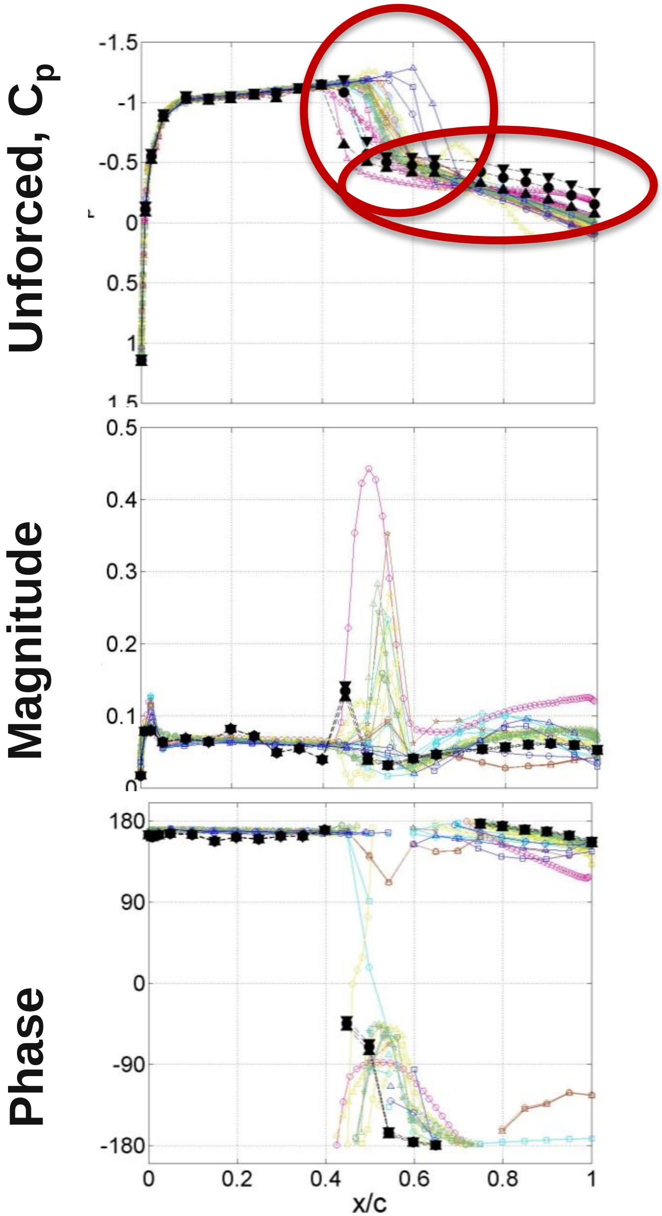


Experiment:
black symbols
Computations:
one color per analysis team

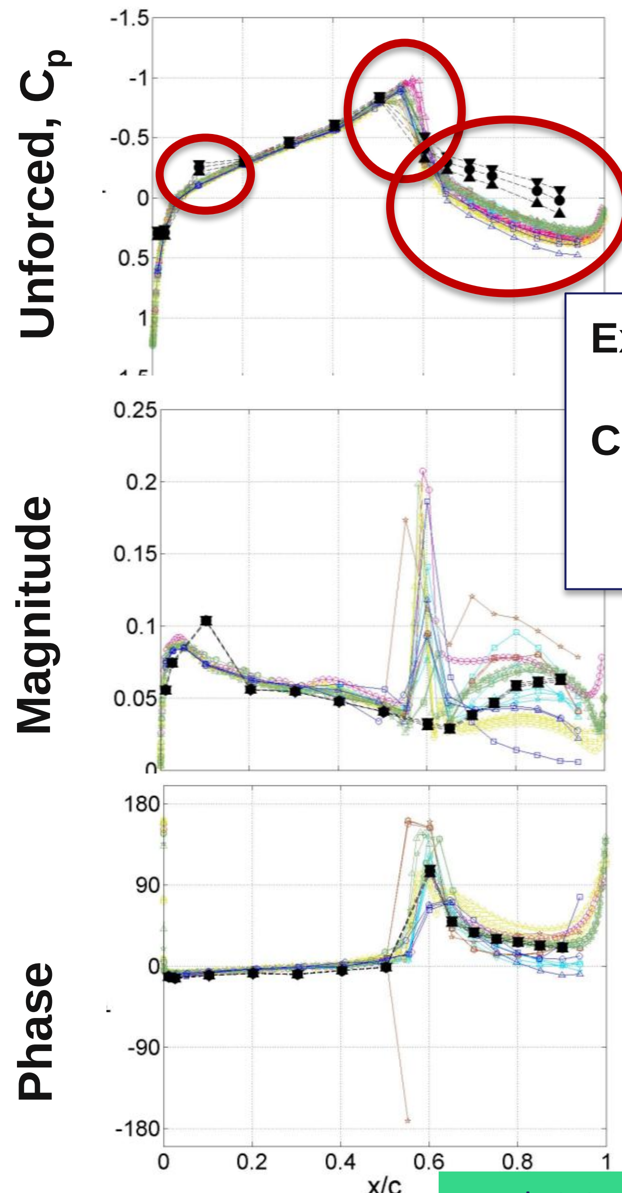
Mach 0.85, $\alpha = 5^o$, q = 170 psf, 10 Hz

AePW Results

Upper Surface



Lower Surface



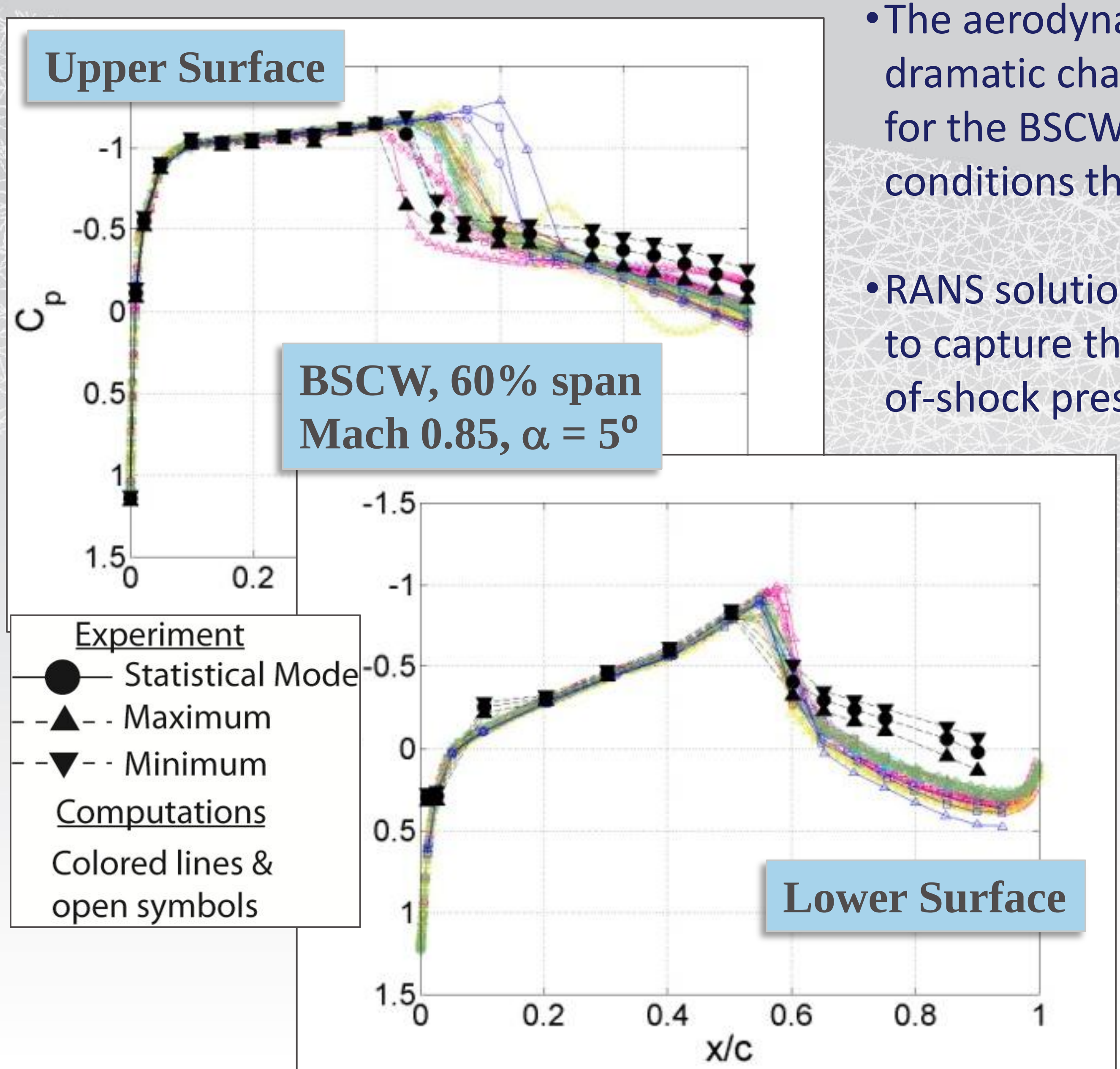
Experiment:
black symbols
Computations:
one color per analysis team

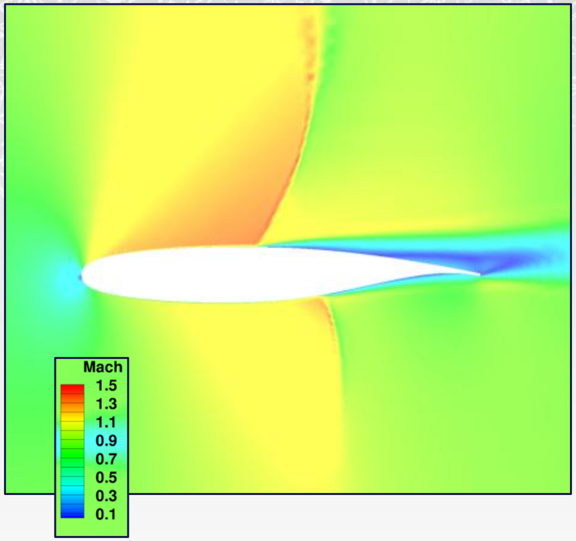
Mach 0.85, $\alpha = 5^o$, q = 170 psf, 10 Hz

Higher fidelity simulations (> RANS) required for separated flow case

- The aerodynamic behavior shows a dramatic change in experimental data for the BSCW configuration for conditions that are post-separation

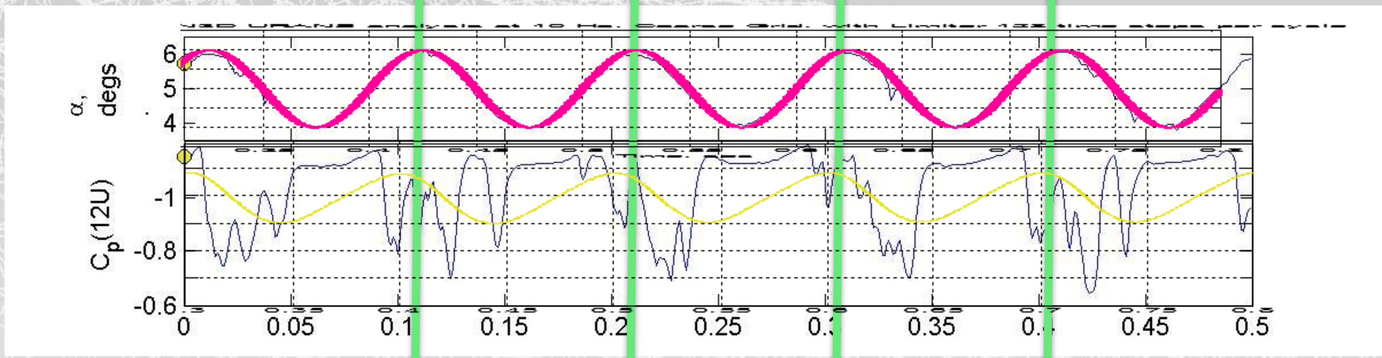
- RANS solutions have NOT been able to capture the shock location or aft-of-shock pressure distributions





Comparison of behavior at Mach 0.85, Experiment & URANS

Mach 0.85



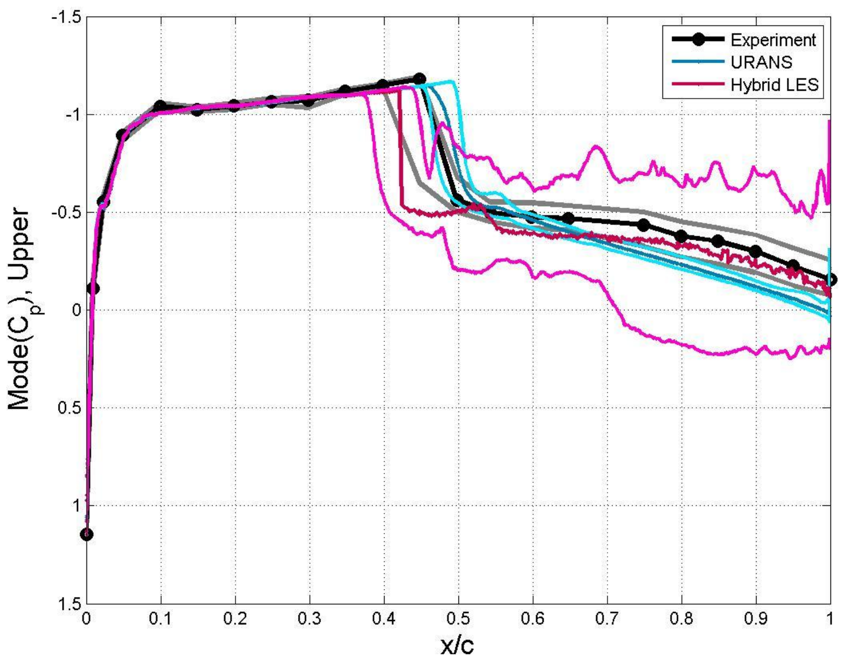
Experiment: blue
Computation: yellow Cp
Coarse grid, with flux limiter, coarse time step, last cycles of computational results

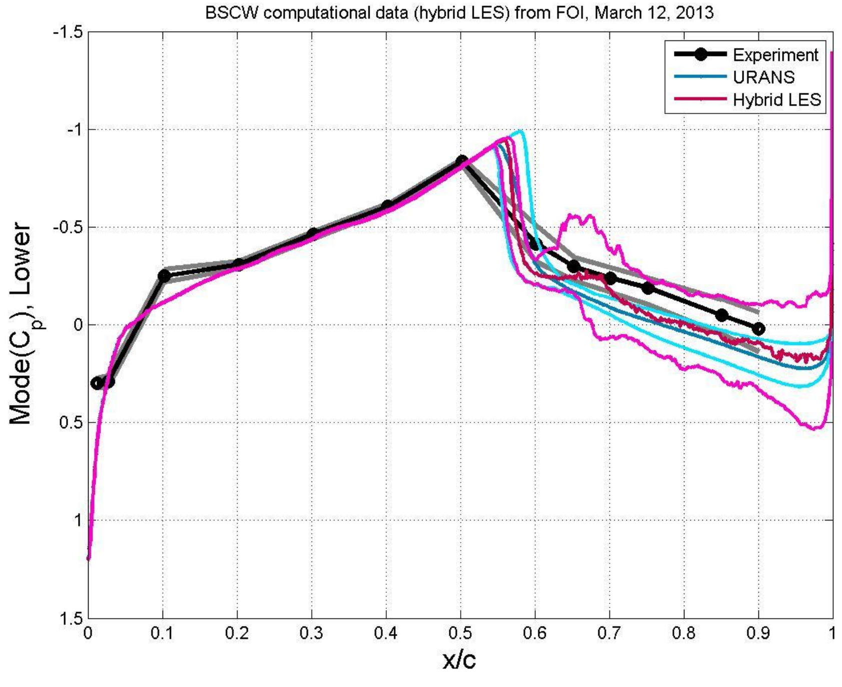
During the cycle when the angle of attack is highest:

Exp: Sensor is aft of the shock leading edge; shock has oscillated forward

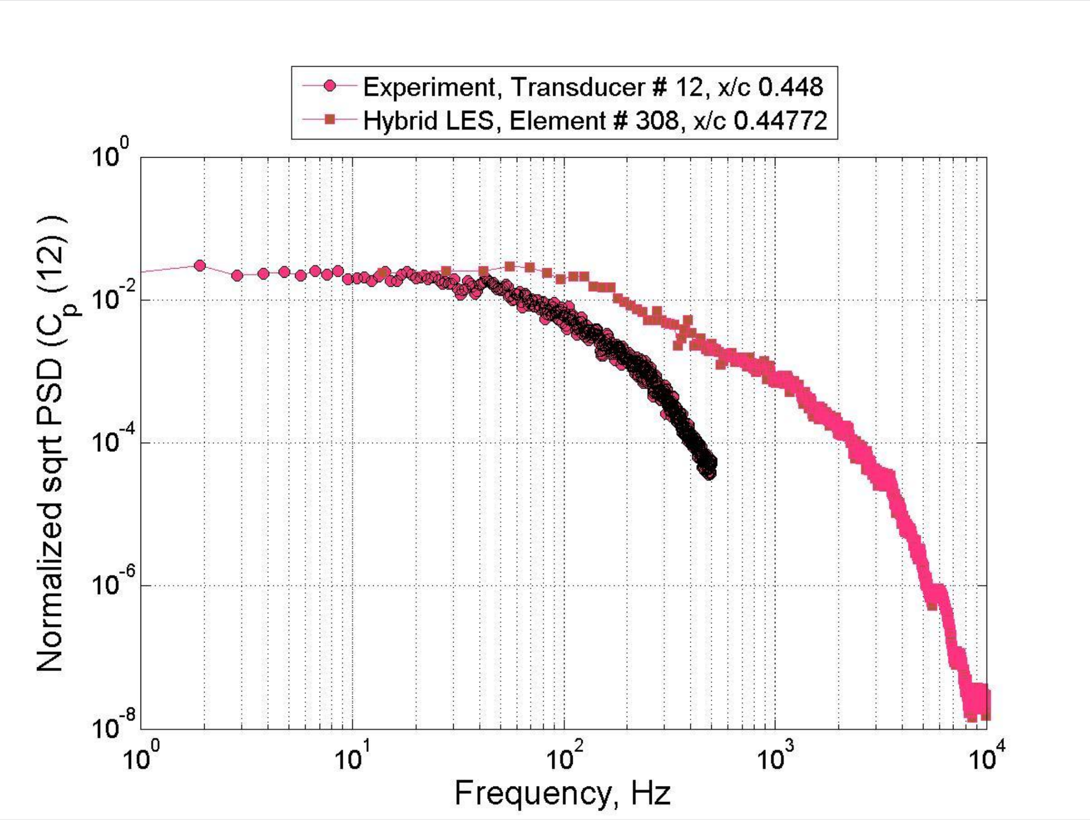
Computation: Sensor is at its highest value, i.e. as close to the shock leading Edge as it will ever get; shock is at its aft-most location when angle of attack is highest

Preliminary Results from applying higher fidelity method





Frequency domain analysis of preliminary higher fidelity method results



Problems in performing comparisons:

Experimental data acquired with a lower sample rate

Computational data acquired for a shorter time record

Applying Fourier analysis methods to nonlinear time histories

Outline

- Workshop overview
- Overview of lessons learned
- Lessons learned in separated flow simulation & experiments
- **Path forward discussion**

Some Potential Paths Forward

- Industry perspective on critical needs
- Extension to aeroelastic analysis
- Higher fidelity methods
- Validation experiment definition
- Extending use of existing experimental data sets

Workshop Summary

- Data for all configurations is public-domain
- Configuration & test case selection based on compromises in simplicity & complexity
- Computational team participation was diverse
- RSW configuration & data set final report generated
- We are working to plan the path forward

Thank you

For listening and being a kind audience

and

To Paul Taylor for presenting this material

Gridding Acknowledgements

Lead	Organization	Configuration	Software	Description
Marilyn Smith	**Georgia Tech**	RSW	SolidMesh	Unstructured
Thorsten Hansen	**Ansys Germany**	RSW, BSCW	ICEM CFD	Structured hexahedral
Pawel Chwalowski	**NASA**	RSW, BSCW, HIRENASD	VGRID	Unstructured mixed and tetrahedral
Eric Blades	**ATA Engineering**	BSCW	SolidMesh	Unstructured, node-based, mixed
Markus Ritter	**DLR**	HIRENASD	Centaur Solar	Unstructured mixed
Daniella Raveh	**Technion**	HIRENASD		Overset structured

AePW Reference Publications

IFASD 2011, Paris

- Heeg, J.; et al, "Plans for an Aeroelastic Prediction Workshop," IFASD-2011-110, International Forum on Aeroelasticity & Structural Dynamics, June 2011, Paris.
- Chwalowski, P., Florance, J., Heeg, J., Wiseman, C., and Perry, B, "Preliminary computational results of HIRENASD configuration in preparation for the Aeroelastic prediction Workshop," IFASD_2011-108, June 2011, Paris.
- Hassan, David, and Ritter, Markus, "Assessment and prediction capabilities for numerical aeroelasticity based on HIRENASD configuration," IFASD-2011-109, June 2011, Paris.

ICCFD 2012, Hawaii

- Schuster, D., Chwalowski, P., Heeg, J., and Wieseman, C., "Summary of data and findings from the First Aeroelastic Prediction Workshop," Tech. rep., Hawaii, 2012, 7th International Conference on Computational Fluid Dynamics, ICCFD7-2012.

AIAA ASM 2013, Grapevine Texas

- Heeg, J., Chwalowski, P., Florance, J.P., Wieseman, C.D., Schuster, D.M., and Perry, B. III, "Overview of the Aeroelastic Prediction Workshop," AIAA 2013-0783, 51st AIAA Aerospace Sciences Meeting, January 7-10, 2013, Grapevine, Texas.
- Schuster, D.M., Heeg, J., Wieseman, C.D., and Chwalowski, P., "Analysis of test case computations and experiments for the Aeroelastic Prediction Workshop," AIAA-2013-0788.
- Mavriplis, D.J., Yang, Z., and Long, M., and Sitaraman, J., "Results using NSU3D for the First Aeroelastic Prediction Workshop," AIAA 2013-0786, 51st AIAA Aerospace Sciences Meeting, January 7-10, 2013, Grapevine, Texas.
- Raveh, D.E., Yossef, Y.M. and Levy, Y, " Flow simulations for the first Aeroelastic Prediction Workshop using the EZNSS code," AIAA 2013-0787, 51st AIAA Aerospace Sciences Meeting, January 7-10, 2013, Grapevine, Texas.
- Chwalowski, P., Heeg, J., Wieseman, C.D., and Florance, J.P., "FUN3D analyses in support of the First Aeroelastic Prediction Workshop," AIAA 2013-0785, 51st AIAA Aerospace Sciences Meeting, January 7-10, 2013, Grapevine, Texas.
- Heeg, J., Chwalowski, P., Wieseman, C.D., Florance, J.P., and Schuster, D.M., "Lessons learned in the selection and development of test cases for the Aeroelastic Prediction Workshop: Rectangular Supercritical Wing," AIAA-2013-0784, 51st AIAA Aerospace Sciences Meeting, January 7-10, 2013, Grapevine, Texas.

AIAA SDM 2013, Boston

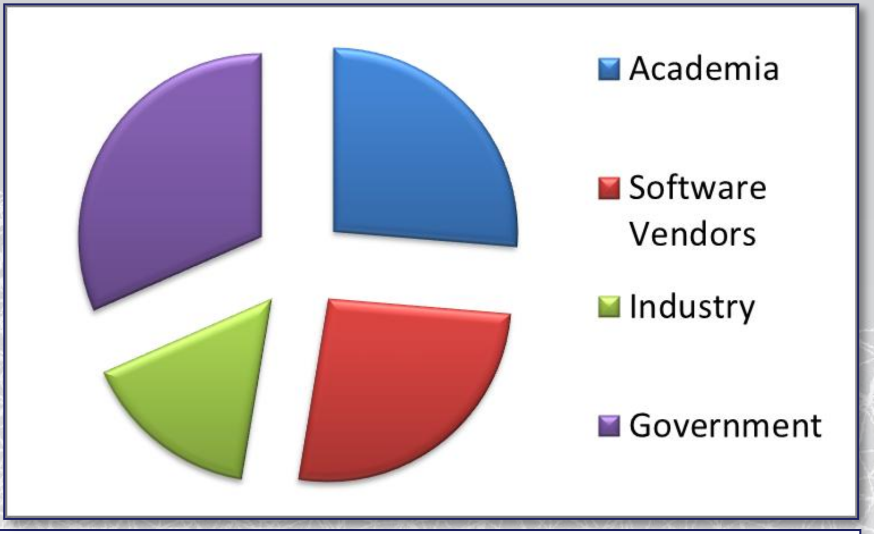
- Heeg, J., Chwalowski, P., Schuster, D.M., and Dalenbring, M., "Overview and lessons learned from the Aeroelastic Prediction Workshop," AIAA 2013-1798, 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, Massachusetts, Jan. 8-11, 2013.
- Dalenbring, M., Jirasek, A., Chwalowski, P., et al. "Initial Investigation of the BSCW Configuration using Hybrid RANS-LES modeling," AIAA-2013-1799.
- Nikbay, M. and Acar, P., "Steady and unsteady aeroelastic computations of HiReNASD wing for low and high Reynolds numbers," AIAA-2013-1800.
- Wieseman, C., Chwalowski, P., Heeg, J., Boucke, A., and Castro, J., "Structural Dynamics Modeling of HIRENASD in Support of the Aeroelastic Prediction Workshop," AIAA-1801.
- Heeg, J., and Piatak, D. , "Experimental data from the benchmark super-critical wing wind tunnel test on an oscillating turntable", AIAA-2013-1802.

Backup Material

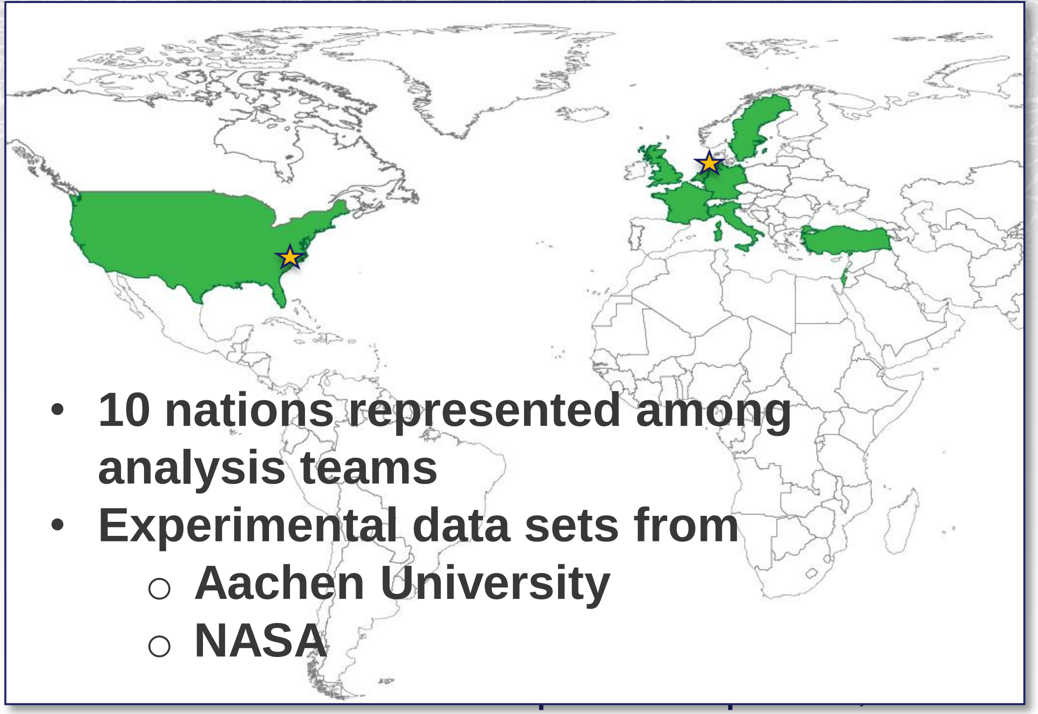
Workshop Contributors

- 17 analysis teams providing analysis results for workshop
- 26 total analysis sets provided for workshop

RSW	BSCW	HIRENASD
6	6	14



- 59 registered attendees
- Organized by a committee of 19 government, industry, and university aeroelastic specialists representing both the United States and Europe



- **10 nations represented among analysis teams**
- **Experimental data sets from**
    - **Aachen University**
    - **NASA**

AePW Analysis Teams

Affiliation	Analysis Team Members	RSW	BSCW	HIRENASD
NASA	Pawel Chwalowski	x	x	x
ANSYS Germany GMBH	Thorsten Hansen, Angela Lestari	x	x	x
University of Wyoming	Dimitri Mavriplis, Mike Long, Zhi Yang, Jay Sitaraman	x	x	x
RUAG Aviation	Alain Gehri, Daniel Steiling	x	x	x
NASA	David Schuster, Andrew Prosser	x	x	
Swedish Defense Research Agency, FOI	Mats Dalenbring, Adam Jirasek		x	x
Technion University IIT	Daniella Raveh		x	x
Georgia Institute of Technology	Marilyn Smith, Benn Mann		x	
University of Liverpool	Sebastian Timme	x		
NLR	Bimo Pranata, Bart Eussen Jaap van Muijden			x
ONERA	Anne-Sophie Sens, Jean-Pierre Grisval			x
DLR	Markus Ritter			x
Istanbul Technical University & ZONA Technology, Inc.	Melike Nikbay, Pinar Acar, Cagri Kilic, Zhichao Zhang			x
Politecnico de Milano	Sergio Ricci, Andrea Parrinello, Giulio Romanelli			x
MSC and Metacomp	Jack Castro, Beerinder Singh			x
Boeing Research & Technology	Mori Mani, Andrew Cary, Larry Brase			x*
CD-Adapco	Alain Mueller, Sergey Zhelzov			x*

* Analyses performed were different from those required for comparison with other AePW datasets.

Organizing Committee Roster

Name	Affiliation
Bhatia, Kumar	Boeing Commercial Aircraft
Ballmann, Josef	Aachen University
Blades, Eric	ATA Engineering, Inc.
Boucke, Alexander	Aachen University
Chwalowski, Pawel	NASA
Dietz, Guido	European Transonic Windtunnel (ETW)
Dowell, Earl	Duke University
Florance, Jennifer	NASA
Hansen, Thorsten	ANSYS Germany GmbH
Heeg, Jennifer	NASA
Mani, Mori	Boeing Research & Technology
Mavriplis, Dimitri	University of Wyoming
Perry, Boyd	NASA
Ritter, Markus	Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Schuster, David	NASA
Smith, Marilyn	Georgia Institute of Technology
Taylor, Paul	Gulfstream Aerospace
Whiting, Brent	Boeing Research & Technology
Wieseman, Carol	NASA

Acknowledgments

Workshop sponsorship and organization

AIAA Structural Dynamics Technical Committee

AIAA Structural Dynamics Conference Team

Product managers

K.C Niedermeyr and Elizabeth Carter

Event planner Cathy Chenevey

NASA Engineering & Safety Center

Funding of NASA participation,
geometry generation & workshop organization

NASA Subsonic Fixed Wing Program

HIRENASD Research Project

Aachen University

HIRENASD Project Funding

German Research Foundation (DFG)

Grid Generation

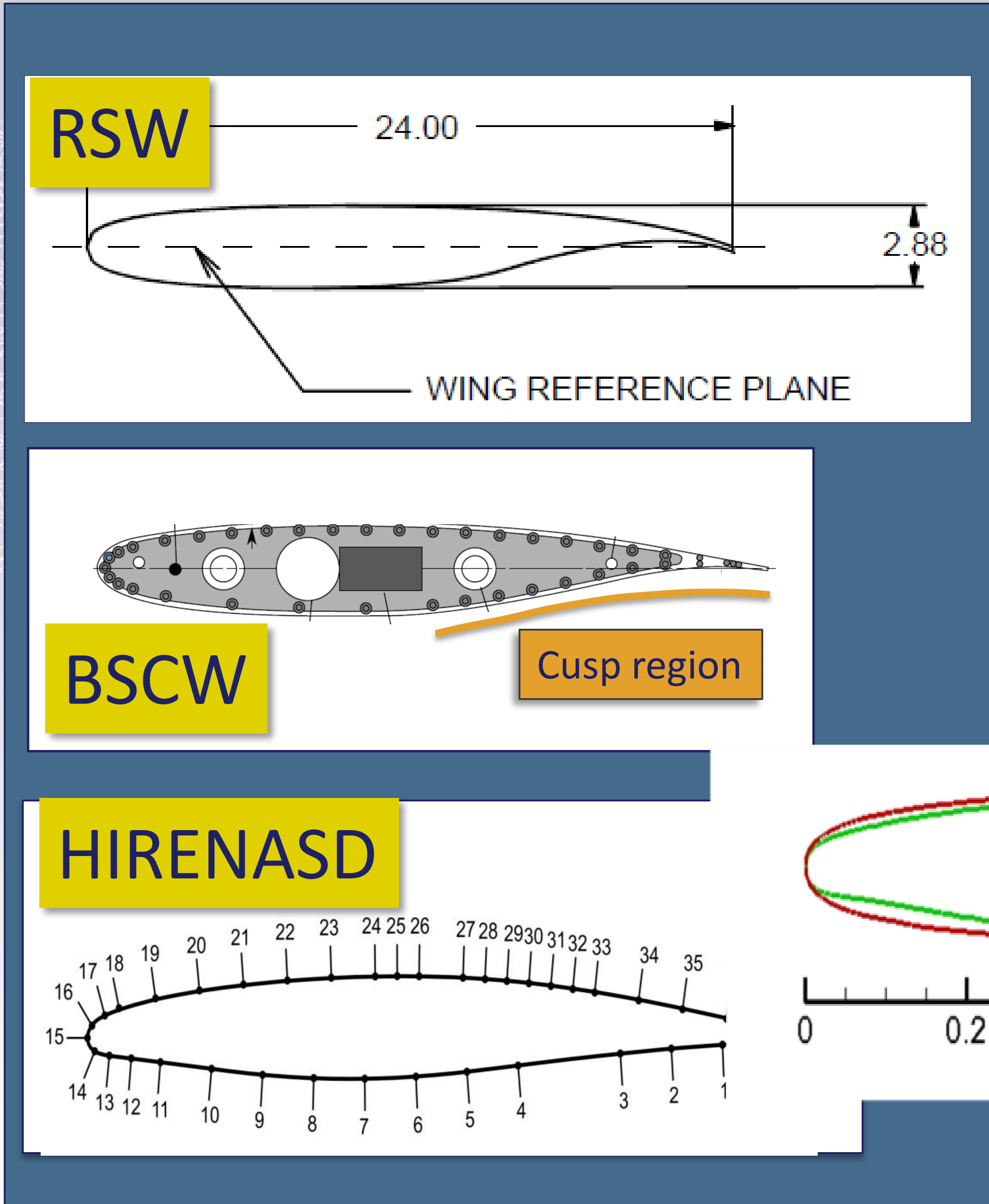
Ansys, ATA, Georgia Tech, Technion University, ISCFDC, NASA, DLR

Test conditions used for illustration in this presentation

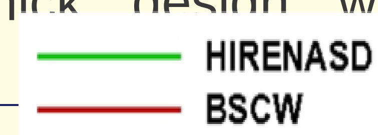
Config	Mach	α	Re_c, millions	Excitation freq, Hz	Airfoil
RSW	0.825	2	4	10	12% thick airfoil modified from an 11% thick design with design point Mach 0.8, C_L 0.6
BSCW	0.85	5	4.5	10	SC(2)-0414
HIRENASD	0.8	1.5	7	80	BAC 3-11

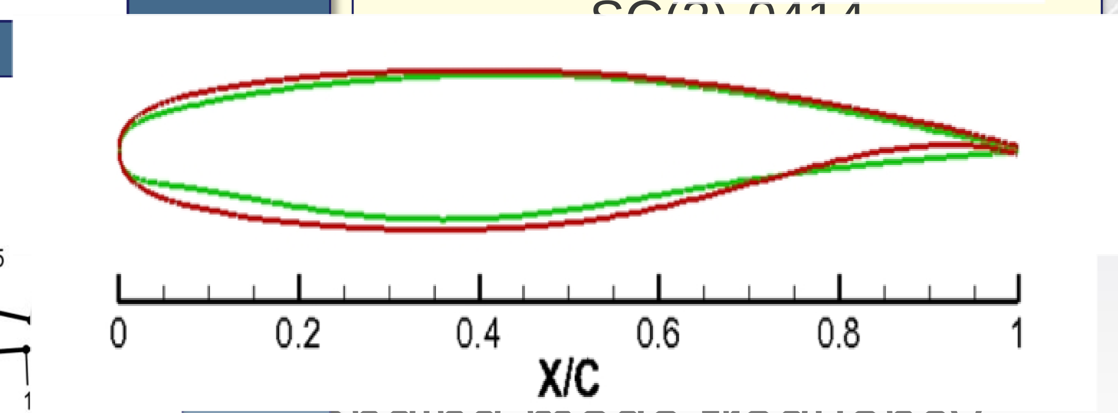
RSW & BSCW: Excited in pitch motion
HIRENASD: Excited at 2^{nd} bending mode frequency

…illustration in this …on



Airfoil
12% thick airfoil modified from an 11% thick design with design point …6
SC(2) 0414





…ending mode frequency

Comparison Data Matrix

CONFIGURATION	REQUIRED CALCULATIONS			
	GRID CONVERGENCE STUDIES	TIME CONVERGENCE STUDIES	STEADY CALCULATIONS	DYNAMIC CALCULATIONS
Steady-Rigid Cases (RSW, BSCW)	C_L, C_D, C_M vs. $N^{-2/3}$	n/a	• Mean C_p vs. x/c • Means of C_L, C_D, C_M	n/a
Steady-Aeroelastic Cases (HIRENASD)	C_L, C_D, C_M vs. $N^{-2/3}$	n/a	• Mean C_p vs. x/c • Means of C_L, C_D, C_M • Vertical displacement vs. chord • Twist angle vs. span	n/a
Forced Oscillation Cases (all configurations)	• Magnitude and Phase of CL, CD, CM vs. $N^{-2/3}$ at excitation frequency	•Magnitude and Phase of C_L, C_D, C_M vs. dt at excitation frequency	n/a	• Magnitude and Phase of C_p vs. x/c at span stations corresponding to transducer locations • Magnitude and Phase of C_L, C_D, C_M at excitation frequency • Time histories of C_p's at a selected span station for two upper- and two lower-surface transducer locations

RSW Flow Solution Information

Analysis Team	Software Name	Turbulence Model*	Flux Construction	Flux Limiter	Oscillatory Solution Method
A	NSMB	SA	Unknown	None	Elastic+TFI
B	FUN3D	SA	Roe	Venkat	Elastic
C	CFL3D	SA	Roe	None	Modal+TFI
D	ANSYS CFX	SST	2nd Order Upwind/ Rhie Chow	Barth & Jesperson	Diffusion equation
E	NSU3D	SA	Matrix Artificial Dissipation	None	Full grid motion
F	PMBv1.5	SA	Osher	MUSCL+ van Albada	Full grid motion

BSCW Flow Solver Information

Analysis Team	Software Name	Turbulence Model*	Flux Construction	Flux Limiter
A	NSMB	SA	Unknown	None
B	FUN3D	SA	Roe	Venkat
C	CFL3D	SA	Roe Flux difference splitting	None
D	NSU3D	SA	Central difference with matrix dissipation	Unknown
E	ANSYS CFX	SST	2^{nd} Order Upwind\ Rhie Chow	Barth & Jesperson

HIRENASD flow solver information

Analysis Team	Software Name	Turbulence Model*	Flux Construction	Flux Limiter
A	ENFLOW	k-ω	Central difference with artificial dissipation	TVD
B	NSMB	k-ω	unknown	None
C	CFD++\ NASTRAN	k-ε	HLLC	Compressive-MinMod
D	EZNSS	SA	HLLC	Venkat
E	EDGE EDGE	SA SA	Central difference[1] Roe[2]	None Venkat
F	TAU	SA	Central scheme with scalar dissipation	None
G	elsA	SA	Jameson	None
H	NSU3D	SA	Central difference with matrix dissipation	None
I	ZEUS†	G	Central difference with JST artificial dissipation	None
J	FUN3D	SA	Roe	Venkat
K	ANSYS CFX	SST	2nd Order upwind/ Rhie Chow	Barth & Jesperson
L	ST‡	n/a	unknown	None
M	AeroFoam	SA	Roe + LW	vanLeer

RSW Submitted Grids

Analysis Team	Grid Type*	Element Type†	Solver Type‡	Number of Nodes or Cells, (millions) *Coarse*	*Medium*	*Fine*
A	Str	Hex	Cell	3.38	9.91	27.0
B	Unstr	Mix	Node	2.88	7.07	18.23
C	Str	Hex	Cell	0.18	1.42	11.18
D	Str	Hex	Node	1.91	5.89	15.42
E	Unstr	Mix	Node	2.87	7.07	18.28
F	SMB	Hex	Cell	2.32	6.60	18.63

* Structured (Str), Unstructured (Unstr), Structured MultiBlock (SMB)

† Hexagonal (Hex), Mixed Hexagonal & Tetrahedral (Mix)

‡ Cell-centered (Cell), Node-centered (Node)

BSCW Submitted Grids

Analysis Team	Grid Type*	Element Type†	Solver Type‡	Number of Nodes or Cells, (millions) *Coarse*	*Medium*	*Fine*
A	Str	Hex	Cell	3.79	9.48	30.32
B	Unstr	Mix	Node	2.97	9.01	26.79
C	Str	Hex	Cell	0.14	1.07	8.40
					1.59	
D	Unstr	Mix	Node	2.97	9.01	
E	Str	Hex	Node	1.49	5.03	13.93

* Structured (Str), Unstructured (Unstr), Structured MultiBlock (SMB)

† Hexagonal (Hex), Mixed Hexagonal & Tetrahedral (Mix)

‡ Cell-centered (Cell), Node-centered (Node)

HIRENASD Submitted Grids

Analysis Team	Grid Type*	Element Type†	Solver Type‡	Number of Nodes or Cells, (millions) *Coarse*	*Medium*	*Fine*
A	SMB	Hex	Cell		10.66	
B	Str	Hex	Cell		9.69	
C	Unstr	Mix	Cell	2.93	8.36	24.18
D	SMB	Hex	Cell		12.61	
E	Unstr	Mix	Node	6.50		
	Unstr	Mix	Node	6.36		
F	Unstr	Mix	Node	1.03	2.45	7.21
G	SMB	Hex	Cell	7.20		
H	Unstr	Mix	Node	6.36	19.06	
I	Str	Quad	Cell	0.56		
J	Unstr	Mix	Node	6.36	19.06	56.31
K	Str	Hex	Node		10.03	
L	Unstr	Tet	Node	0.14		
M	Unstr	Mix	Cell	1.63		

Summary of Rectangular Supercritical Wing Entries						
Analyst	A	B	C	D	E	F
CODE	NSMB	FUN3D	CFL3D	ANSYS CFX	NSU3D	PMBv1.5
TURBULENCE MODEL	SA	SA	SA	SST	SA	SAE
GRID TYPE	Str	Unstr	Str	Str	Unstr	Blstr

Str = Structured

Blstr = Block structured

Unstr = Unstructured

RSW Summary points

- CFD solutions vary widely, even for static solution; Not an accurate representation of the CFD state of the art
- Tunnel wall modeling assumptions have a significant impact on the static pressure distribution, unsteady behavior and integrated loads
- Different modeling and oscillation methods: what are the impacts of the different methods? Is this significant? Methods used:
  - Oscillating the entire computational
  - Oscillating one region of the grid relative to the rest of the domain
    - Boundary of fixed/oscillated on the splitter plate
    - Boundary of fixed/oscillated on the wing, near the root
- Definitions of converged solution seem to be subjective. (on the subiteration level, what defines converged?)

Some BSCW summary points, focused on computational results

- Computational methods had difficulty producing converged solutions due to flow field complexity
- Complex flow field also observed in experimental data; Largest magnitude of dynamic behavior appears to represent shock oscillations
- CFD solutions vary widely, even for static solution
- The flow phenomena that appear to be present on the BSCW test case include
  - shock-induced separated flow
  - geometry-induced separated flow
  - shock oscillations even in the steady solution & unforced experiment
- Convergence wrt grid size has not been consistently demonstrated
- Static predictions of pressure distribution (Xducers are at 60% span):
  - Predictions of upper surface shock location vary by 25% of the chord
  - Predicted values of Cp ahead of shock are consistent among analyses and consistent with experimental data
  - If experimental data is taken as gospel, CFD solutions predict shock too far downstream
  - Aft of shock, the magnitude and distribution of the predictions vary and have a different distribution shape from the experimental data
  - Lower surface: aft of the shock predictions begin to fan out; disagree with the experimental data
- The analytical results tend to look more constant wrt frequency of excitation than experimental results
- Computational FRFs in the region of the shock and aft of the shock do not give consistent answers, nor do they match the experiment
- We have an insufficient number of data submitted to assign cause and effect relationships

Some more BSCW summary points, focused on experimental data

- Airfoil pitches nose upward, shock moves forward; airfoil pitches nose downward, shock moves aft **???**
  - Misinterpretation of the data?
  - We've found another sign convention issue or sign error?
  - Something interesting is going on?
- There are several regions on qualitatively different pressure behavior on the airfoil upper surface
  - Leading edge, ahead of transition (noisy sinusoidal data)
  - Between transition strip and shock (sinusoidal data)
  - Shock-traversing region (floor-limited, ceiling-limited fluctuations)
  - Aft of shock region (random + sinusoidal)

- The experimental data is not well-represented by mean values for the static data, particularly in the region of the shock oscillation
- The frequency response functions obtained at a single frequency do not necessarily represent the significant physics, particularly the oscillatory shock and the separated flow
- The experimental data needs to be more closely spaced; particularly in the region of the shock.
- The experimental frequency response functions do not have constant or monotonically increasing magnitude wrt oscillation frequency. The system has dynamics within the range of the frequencies investigated. (splitter plate vertical mode clearly contributes to this variation.)
- Methods being used to characterize the flow field:
  - Mean, max, min of non-forced-oscillation data ("steady" data)
  - Histograms and statistical quantities can possibly be useful in characterizing the different flow regions
  - Frequency response functions
  - Coherence (see separate document for details of coherence vs frequency as the chord location is varied- definite changes in behavior ahead of transition strip, ahead of the shock, in the shock motion region, aft of the shock)

HIRENASD summary points

- Convergence results: Difficult to say anything at this point. Experimental comparison data & updates from analysts required
- CFD solutions produce consistent results for the mid-span properties, both statically and dynamically; agreement with experiment is “not so bad”
- Mach 0.7 case used as a benchmark- very benign and qualitatively good comparisons with experimental data
- Neither solver type nor turbulence model appears to differentiate goodness of static solutions; influence on frequency response functions requires more evaluation
- Wing tip region is poorly predicted
- Little attention has been paid to the leading edge suction peak or other behavior. Generally assumed that match would be poor; fully turbulent flow in modeling, forced transition in experimental data.

Thanks to Technical Working Group Leaders

Role:	RSW	BSCW	HIRENASD
Discussion Leader	Dave Schuster	Pawel Chwalowski	Markus Ritter & Dimitri Mavriplis
Technical Issue Recorder	Reik Thormann	Thorsten Hansen	

HIRENASD Project Partners

Aachen University:

Department of Mechanics

Institute for Lightweight Structures

Institute for Geometry and Applied Mathematics

Shock Wave Laboratory

Thanks to ...

- German Research Foundation (***DFG***) for funding ***HIRENASD***
- ***Airbus Industry*** for supporting the balance for dynamic force measurement
- ***DLR*** for advice concerning data acquisition and providing AMIS II
- ***ETW*** for providing windtunnel adaptations, for e.g. dynamic force measurement, and continuous advice during preparation of model and measuring equipment

AePW Analysis Parameters

Parameters		Units		Configuration				
		English	SI	RSW (English units)	BSCW (English units)	HIRENASD (SI units)	HIRENASD (SI units)	HIRENASD (SI units)
Mach number	M			0.826	0.848167	0.8005	0.8	0.7
Reynolds number (based on ref chord)	Re_c			4.01e+06	4.491e+06	6999999	23486600	6997830
Reynolds number per unit	Re/ unit	Re/ft	Re/m	2.0e+06	3.368e+06	2.032e+07	6.8176e+07	2.031e+07
Dynamic pressure	q	psf	Pa	108.65	204.1967	40055.4	88696.9	36177.3
Velocity	V	ft/s	m/s	413.73	468.9833	256.5	219.5	227.0
Speed of sound	a	ft/s	m/s	501.18	552.9333	320.3	274.8	324.3
Static temperature	Tstat	deg F	deg K	37.12	87.913	246.9	181.8	253.1
Density	r	slug/ft^3	kg/m^3	0.001270	0.001857	1.22	3.70	1.41
Ratio of specific heats	g			1.132	1.116233			
Dynamic viscosity	m	slug/ft-s		2.620e-07	2.59E-07			
Prandtl number	Pr			0.78	0.6738	0.72	0.72	0.72
Test medium				R-12	R-134a	Nitrogen	Nitrogen	Nitrogen
Total pressure	H	psf	Pa	410.48	757.31	136180	301915	146355
Static pressure	P	psf	Pa	280.76	512.12	89289	198115	105529
Purity	X	%			95			
Total temperature	T	deg F	deg K	60.00	109.5933	278.5	205.0	277.9

Reference quantities

		RSW	BSCW	HIRENASD
Reference chord	c_{ref}	24 inches	16 inches	0.3445 m
Model span	b	48 inches	32 inches	1.28571 m
Area	A	1152 in^2	512 in^2	0.3926 m^2
Moment reference point, relative to axis system defns	x	11.04 inches	4.8 inches	0.252 m
	y	0	0	-0.610 m
	z	0	0	0
Transfer function reference quantity		Pitch angle	Pitch angle	Vertical displacement (at x=0.87303m, y=1.24521m)

Aeroelastic Data Set Selection for CAE Code Validation

Content of an "Excellent" Data Set

- Configuration that can be modeled minimizing the level of uncertainty in the analysis
- High-quality model definition
  - Well-documented geometry
  - Stiffness, mass, and inertia measurements
  - Structural dynamic properties
    - Natural frequencies
    - Mode shapes
    - Generalized mass
- High-quality wind-tunnel measurements
  - Flow regime: include subsonic, transonic, and supersonic
  - Extensive array of unsteady pressure measurements- due to forced motion
  - Quantitative displacement measurements
  - Quantitative flow visualization measurements
  - Loads measurements
  - Quantitative definition of instability boundaries (LCO, flutter, divergence, buffet, etc.)

AePW Solutions

Configuration	Unforced System: Steady, Rigid	Unforced System: Steady, Static aeroelastic	Unforced System: Time-accurate, Rigid	Forced Oscillation System, Time-accurate solutions: Unsteady aerodynamic	Forced Oscillation System, Time-accurate solutions: Unsteady aerodynamics on deformed static aeroelastic mesh	Forced Oscillation System, Time-accurate solutions: Unsteady aeroelastic response
RSW	✓			✓		
BSCW	✓		✓	✓		
HIRENASD		✓		✓†	✓	✓‡

† Performed only by analysis team HIRENASD-B

‡ Performed by subset of analysis teams

Rectangular Supercritical Wing (RSW)

- Simple, rectangular wing
- Structure treated as rigid
- Static and forced oscillation pitching motion

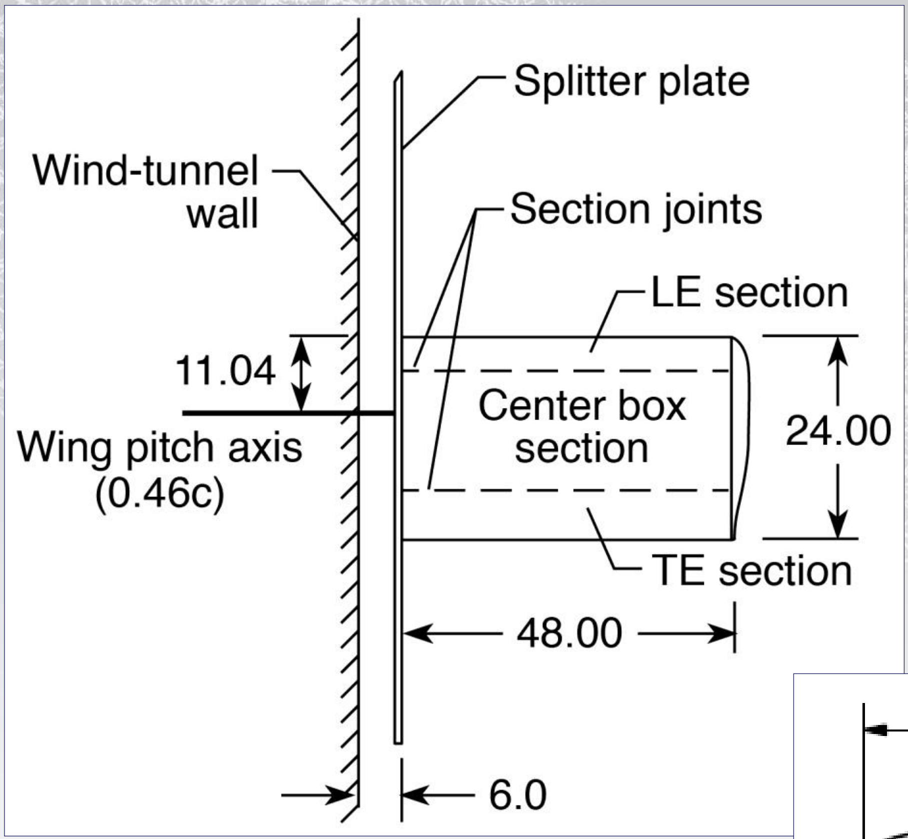
<u>Known deficiencies:</u>

- Splitter plate deficiencies
  - Small size
  - Located in the tunnel wall boundary layer (6" off of the wall)
- Tunnel wall slots open
- Potential bad data points, not identified as such in the literature

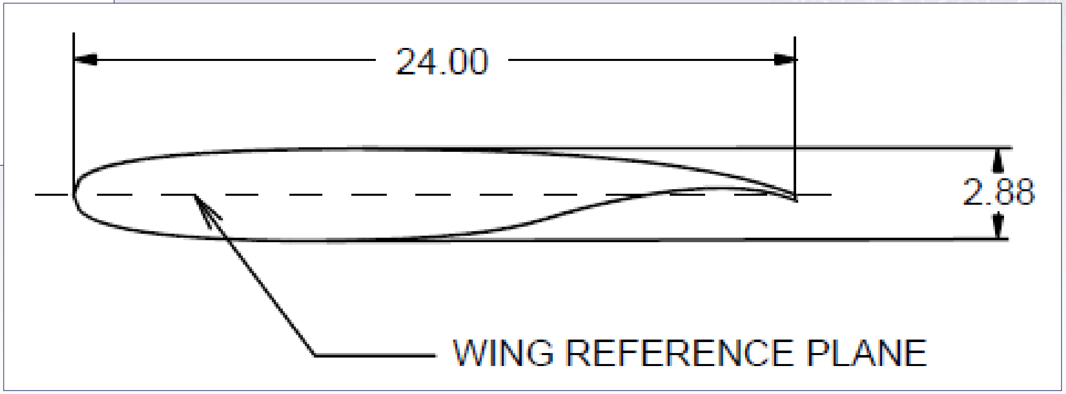
M=0.825, Re_c=4.0 million, test medium: R-12

a) Steady Cases
   i. $\alpha = 2°$
   ii. $\alpha = 4°$
b) Dynamic Cases:
   $\alpha = 2°, \theta = 1°$
   i. f = 10 Hz
   ii. f = 20 Hz

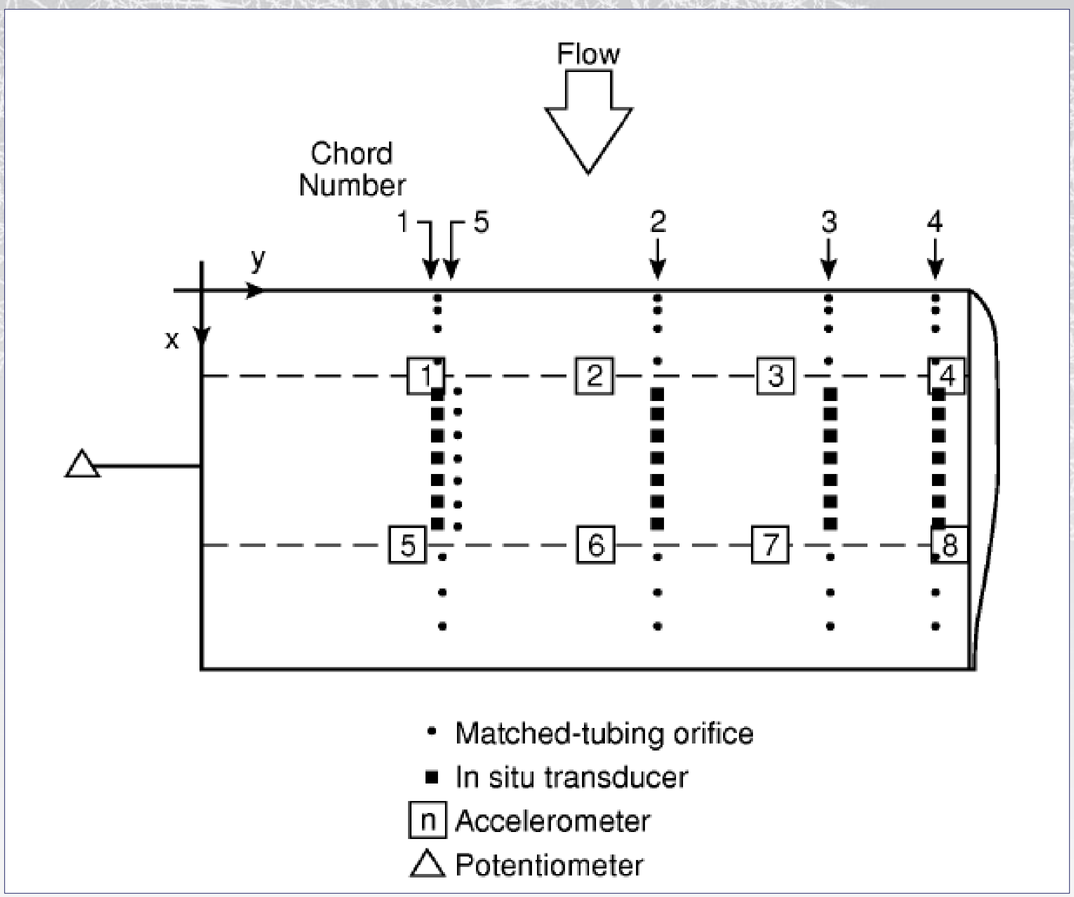
RSW Geometry and Construction



- Unswept, rectangular planform
- Panel aspect ratio = 2
- Tip of revolution
- Leading- and trailing-edge sections attach to center box at 23% and 69% chord
- Supercritical airfoil
  - 12% thick
  - No twist



RSW Instrumentation Layout



Unsteady Pressure Transducers

- **Kulites**
- **4 full chords (1, 2, 3, 4)**
  30.9, 58.8, 80.9, and 95.1 % span
- **29 pressure per chord**
  14 upper, 14 lower, 1 leading edge
- **Center section: in situ**
- **LE & TE sections: matched tubing**

Accelerometers

- **4 along 23% chord**
- **4 along 69% chord**

Potentiometer

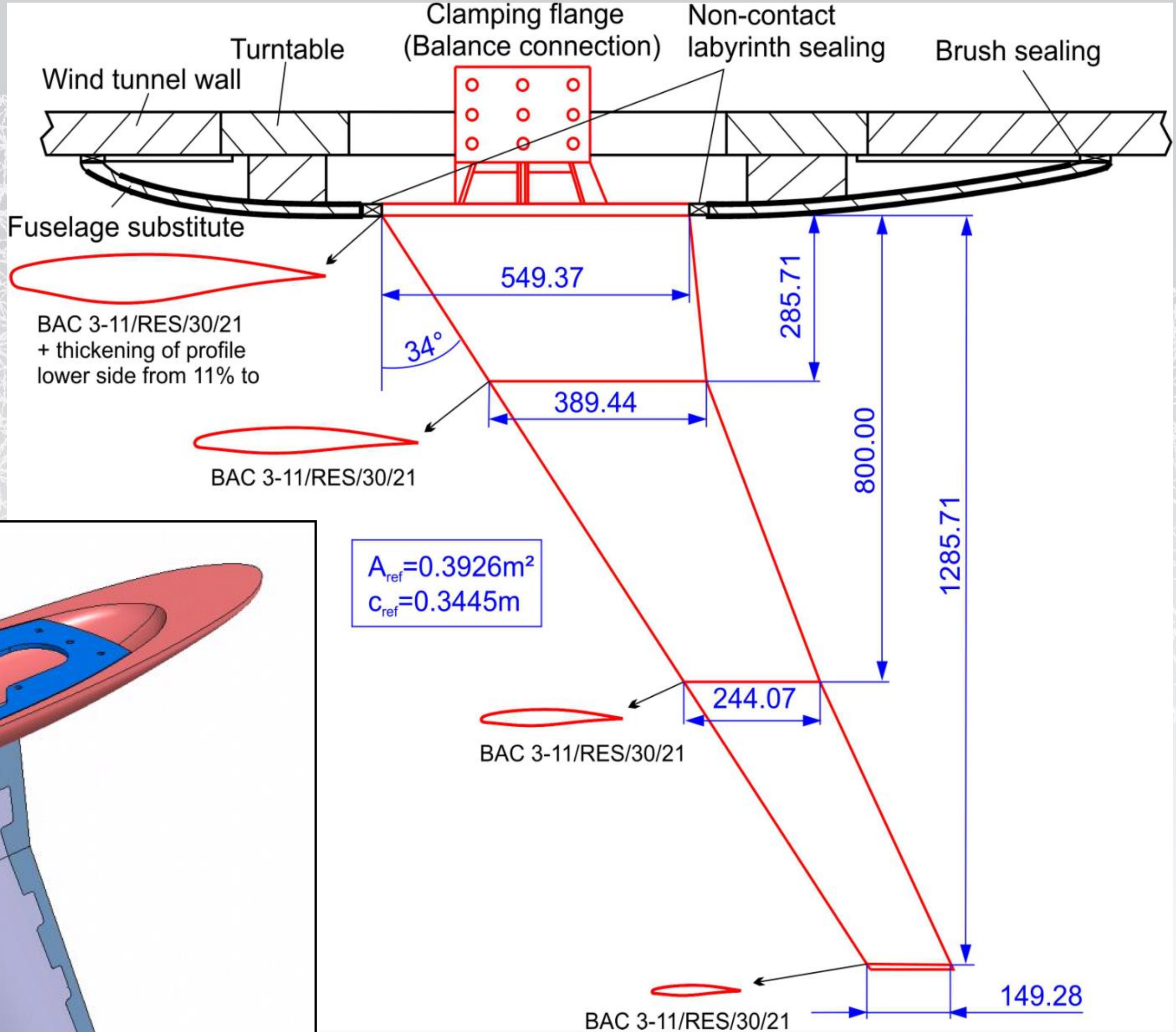
- **1 on pitch axis (46% chord)**

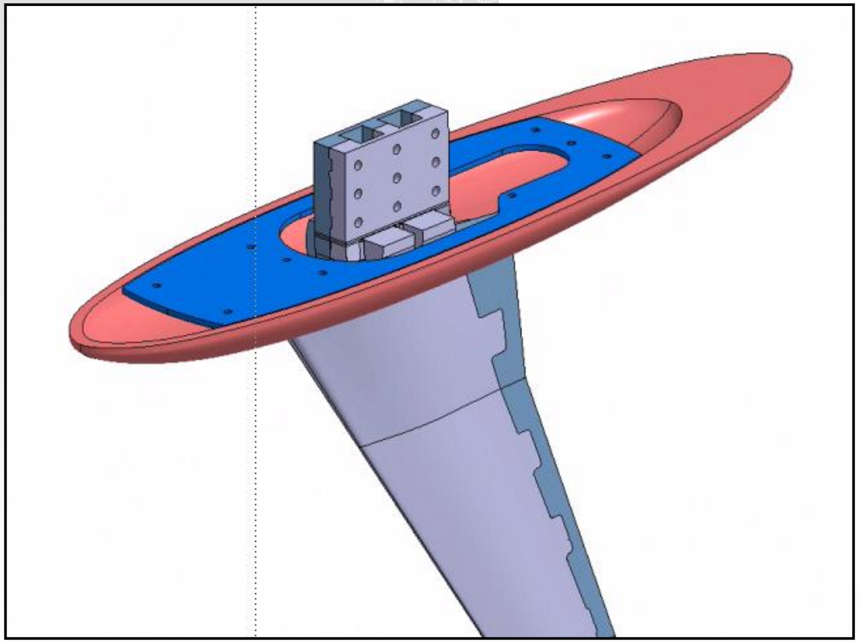
HIRENASD

- Pros:
  - Available FEM, CFD grid, and published experimental data
  - Good distribution of unsteady pressures (259 transducers)
  - Balance loads data
  - Quantitative deformation measurements
  - Accelerometer and strain gage measurements
  - Forced vibration data at 1st and 2nd bending and 1st torsion modes
  - Slightly aeroelastic
  - Transonic conditions with realistic flight Reynolds numbers
  - Additional tests planned
- Cons:
  - No aeroelastic instability data
  - No flow visualization

High Reynolds Number Aero-Structural Dynamics (HIRENASD) Model
Tested in European Transonic Wind Tunnel (ETW), 2006
Funded by Deutsch Forschungsgemeinschaft(DFG)

HIRENASD Layout and Test configuration





HIRENASD Instrumentation

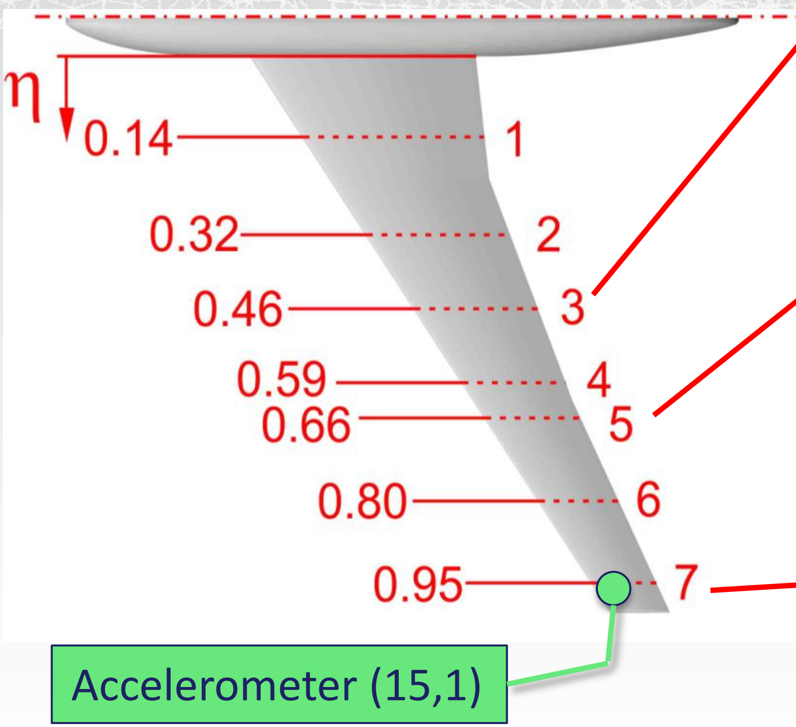
<u>Pressure Sensors:</u>

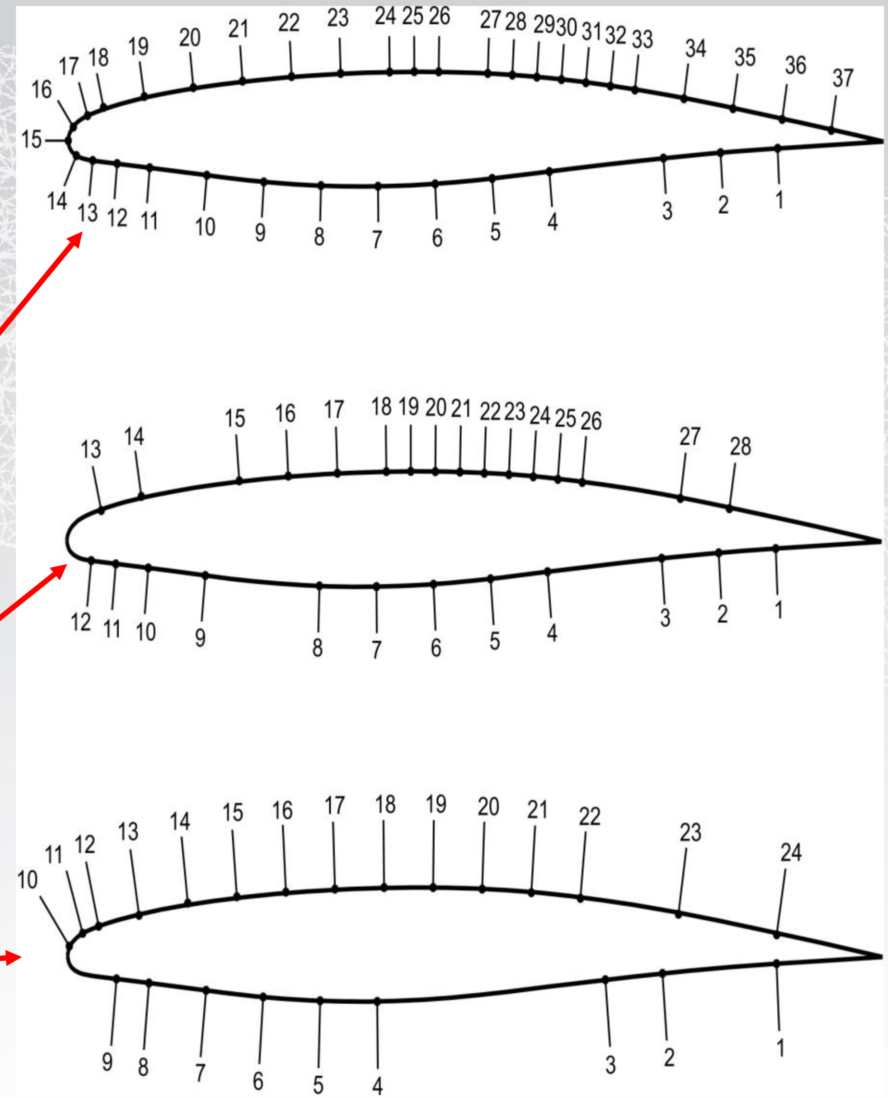
259 in-situ unsteady transducers

7 span stations

<u>Accelerometers:</u>

Utilized only data at outboard location, (15,1)

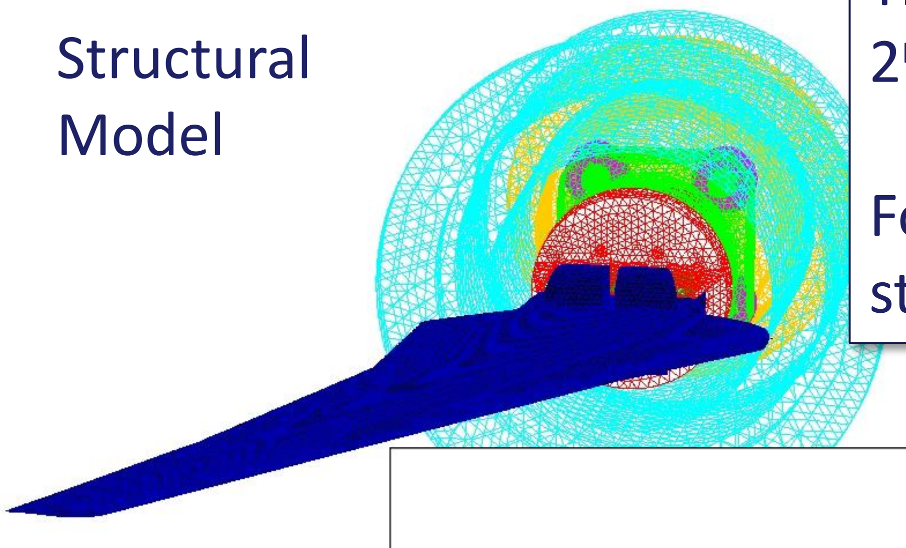




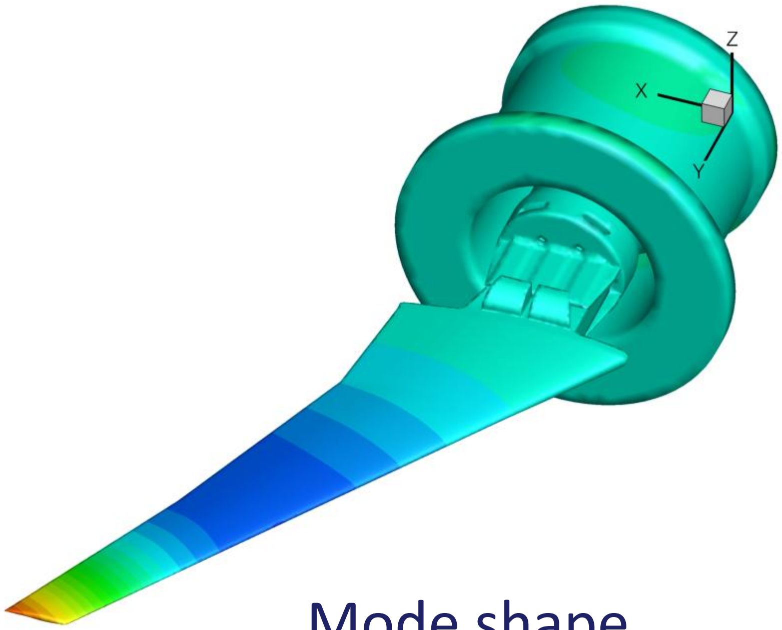
HIRENASD Structural Dynamic Model

The HIRENASD was excited at the 2nd Bending mode frequency, ~80 Hz

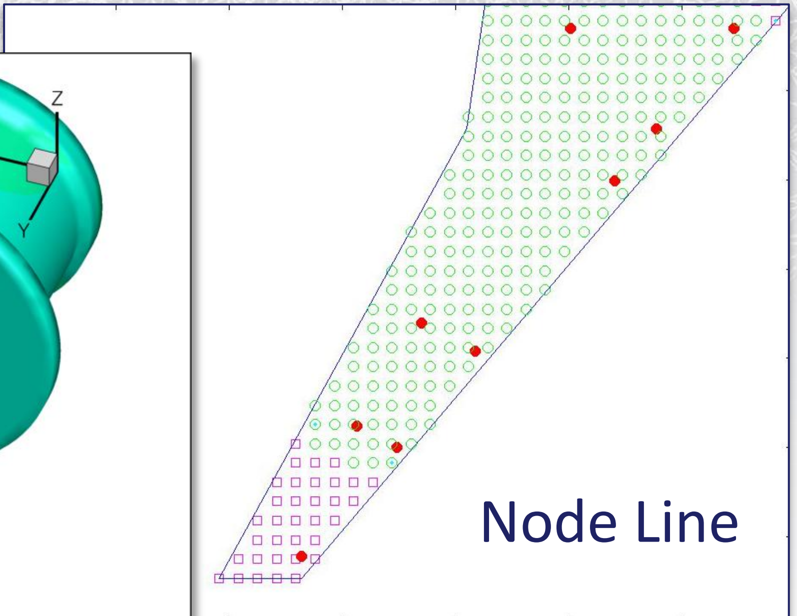
Forces applied using piezoelectric stacks in the mounting hardware



Structural Model



Mode shape, 2nd bending mode



Node Line

HIRENASD Instrumentation

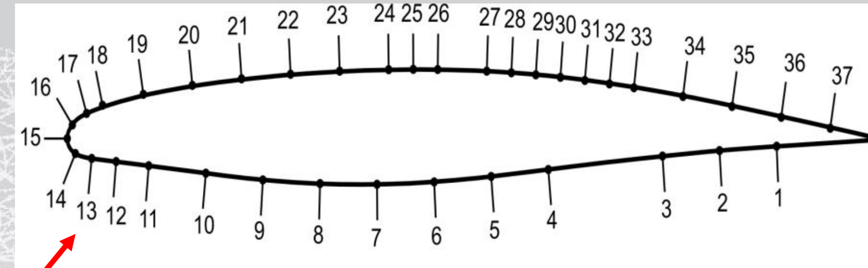
Pressure Sensors:

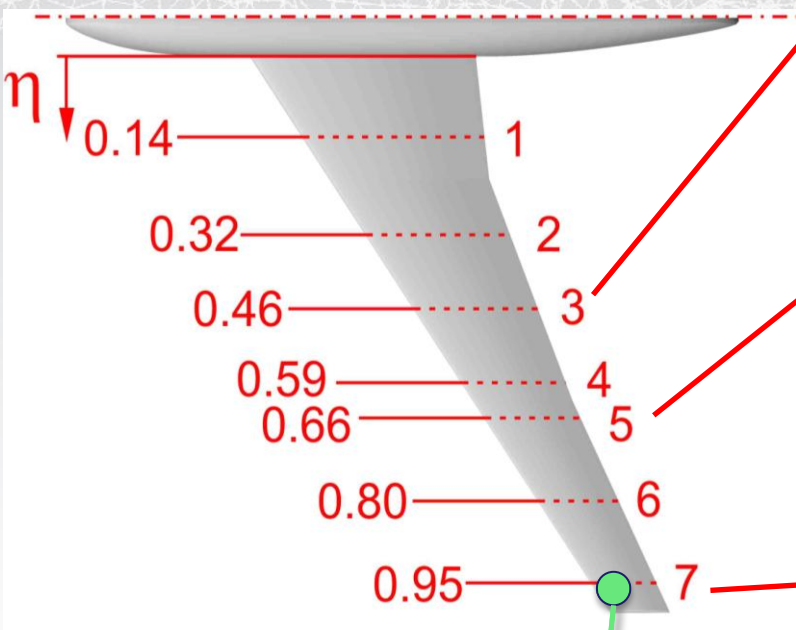
259 in-situ unsteady transducers

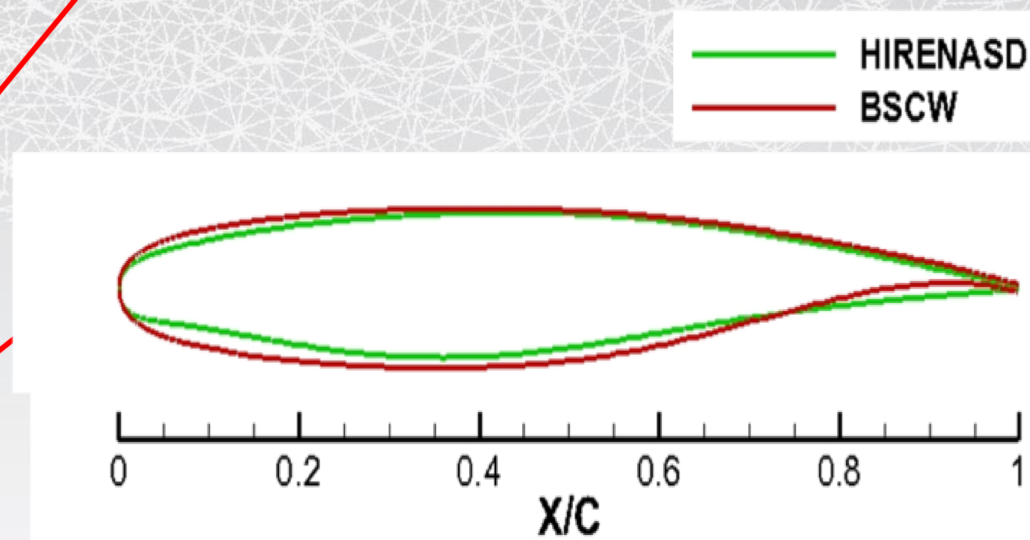
7 span stations

Accelerometers:

Utilized only data at outboard location, (15,1)

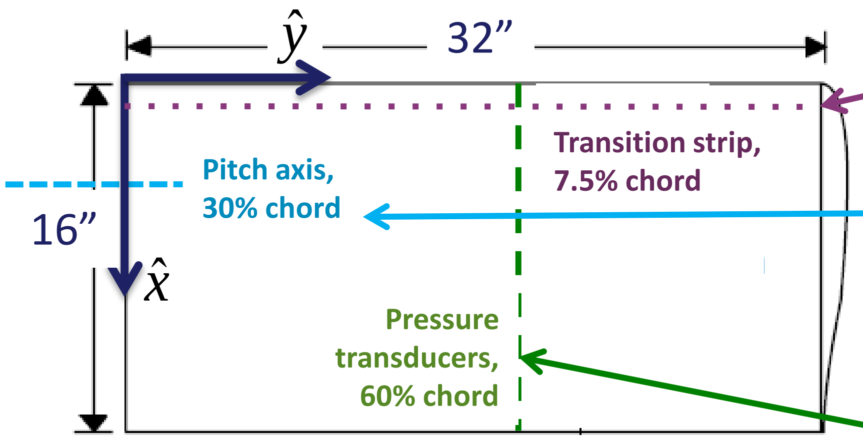






Accelerometer (15,1)

BSCW Test Configuration



Model planform. Dimensions are in inches.

<u>Transition Strip</u>:
7.5% chord

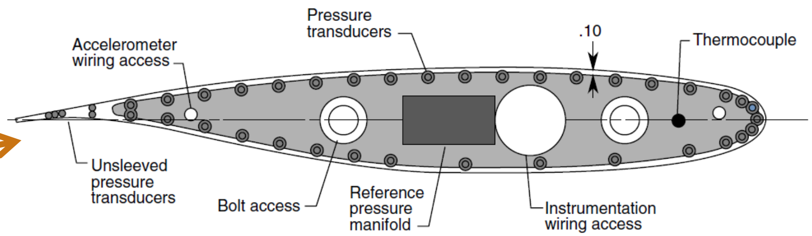
<u>Forced Oscillation</u>:
Pitching motion about 30% chord

<u>Unsteady Pressure Measurements</u>:

- 1 chord fully-populated at 60% span
- Outboard chord at 95% span NOT populated for this test

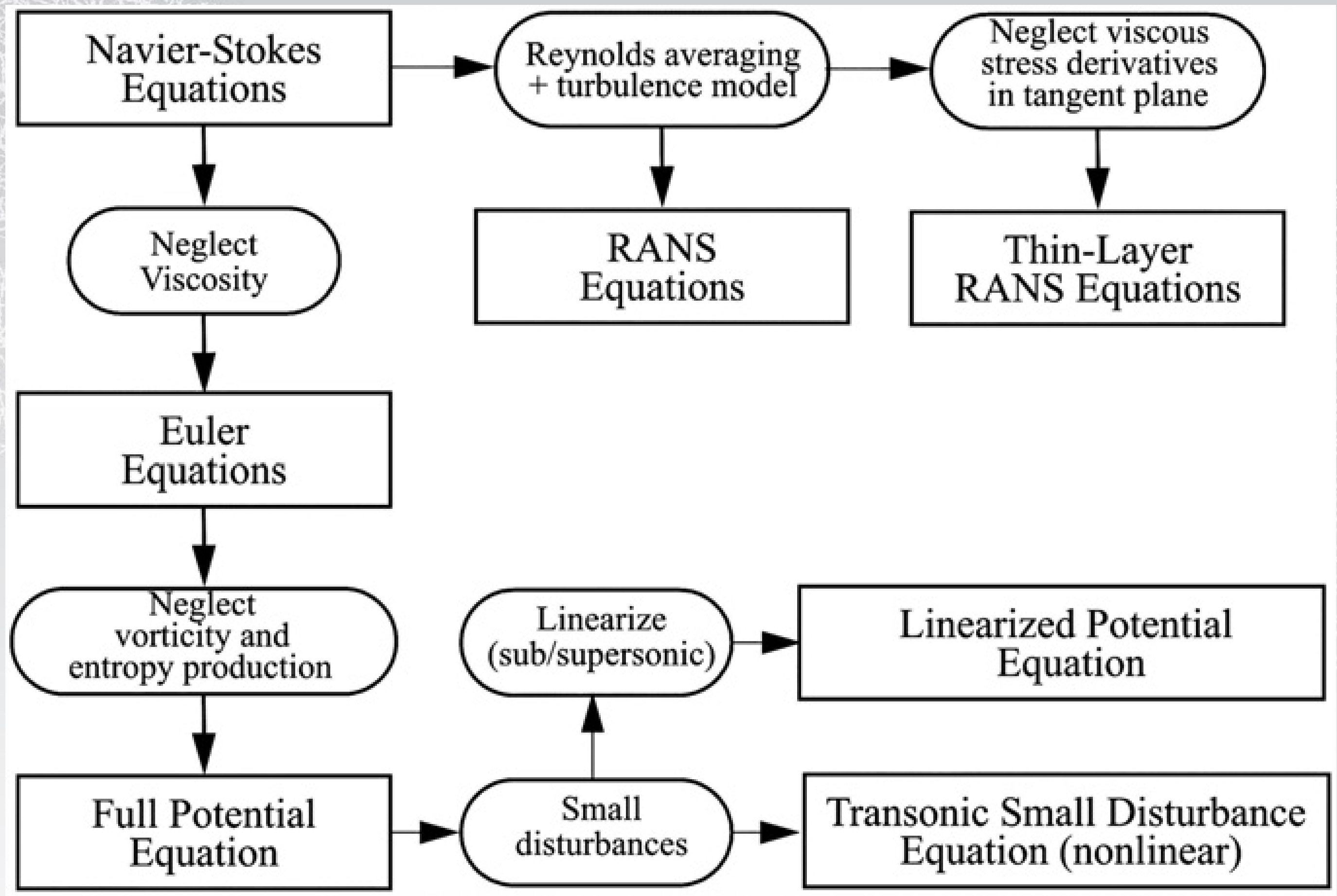
<u>40 In-Situ Unsteady Pressure Transducers</u>:

- 22 upper surface
- 17 lower surface
- 1 leading edge



Cross-section at 60% span, showing the layout of the unsteady pressures.

From Oddvar's unsteady aero paper



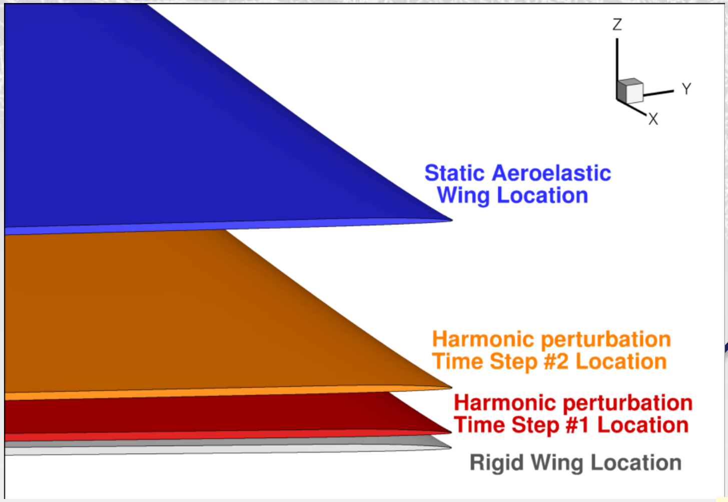
For my personal use only, since I haven't asked Oddvar for permission.

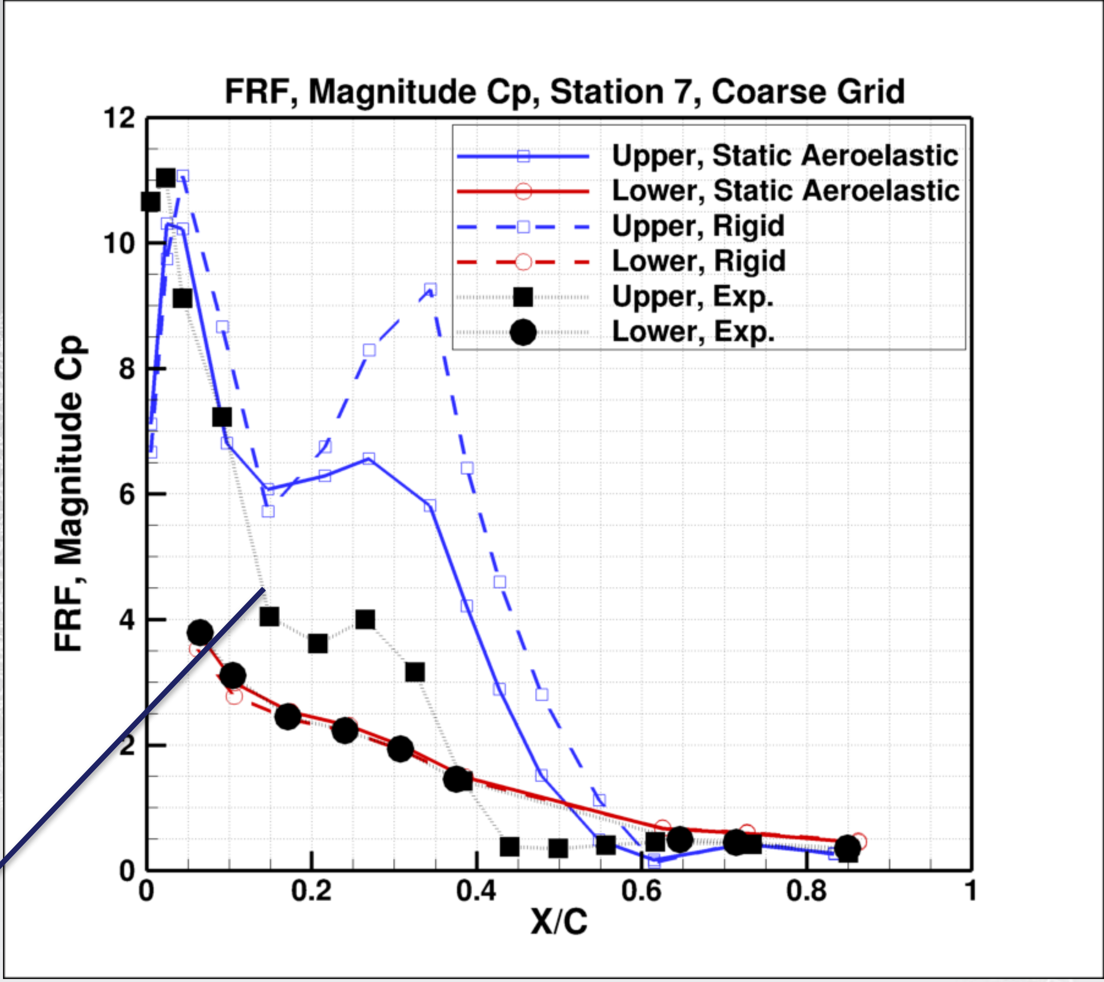
Per Configuration, the biggest lessons learned were…

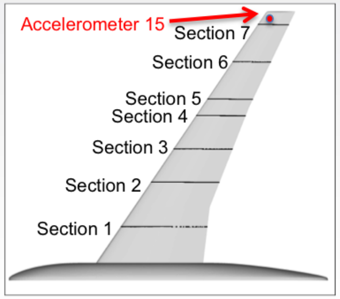
- Wall effects
- Separated flow effects
- Initial cut at studying variations with aeroelastic influences; good benchmarking test case

Influence of static aeroelasticity

Harmonic perturbation around correct initial geometry affects Cp and frequency response function near the wing tip





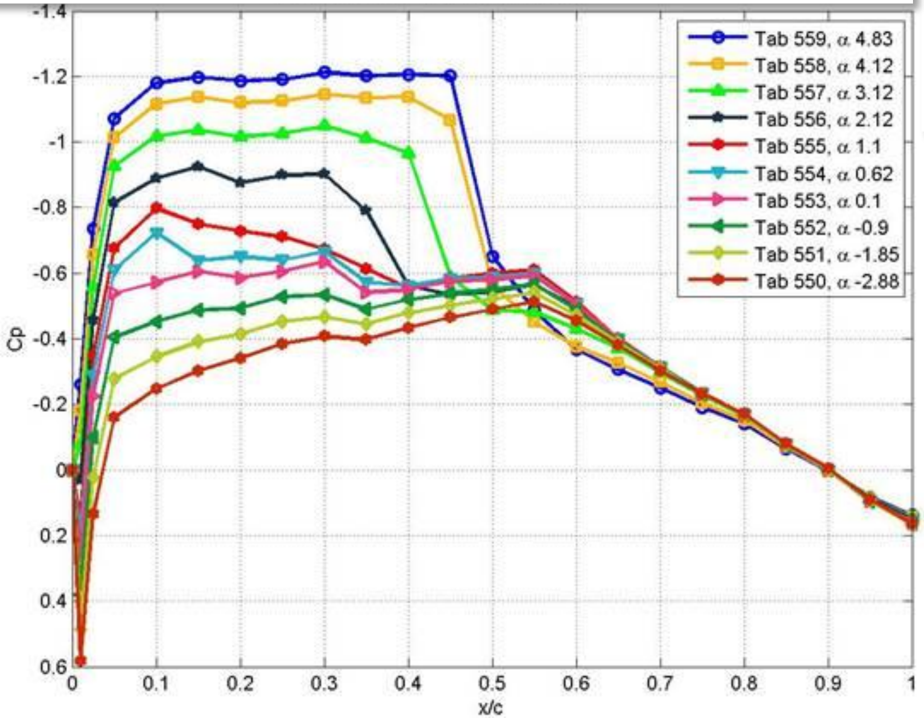


Overprediction of the static pressure distribution
&
Overprediction (larger magnitude of dynamic response)
FRFs show more dynamic response (overprediction) for the rigid wing

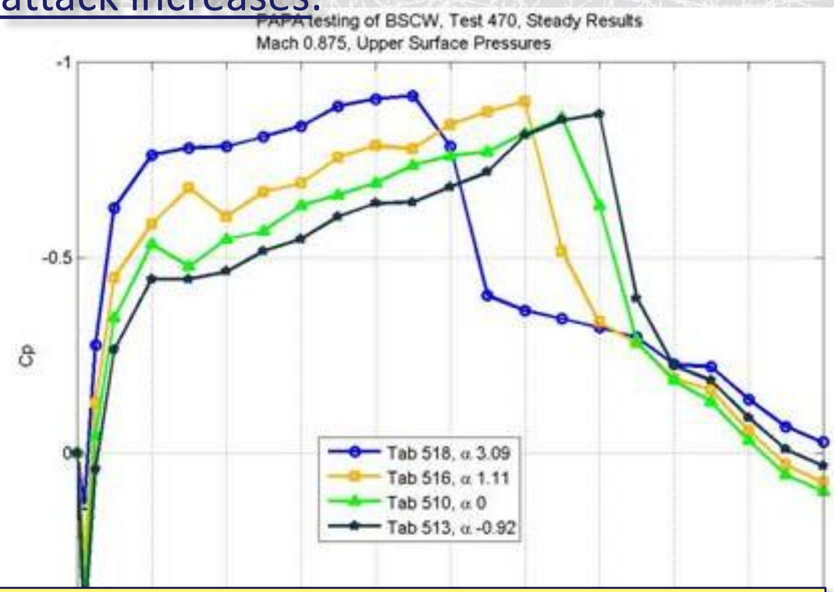
In-depth BSCW experimental data reduction

Prior test data of BSCW configuration on a pitch and plunge apparatus. Unforced system data shows an effect of separation as Mach number increases from Mach 0.8 to 0.875.

At Mach 0.8: Shows shock strengthening and moving towards the trailing edge (aft) as angle of attack increases.



At Mach 0.875, shows the shock strength staying relatively constant and moving towards leading edge (forward) as angle of attack increases.



Note: AePW test condition is Mach 0.85