OVERVIEW AND LESSONS LEARNED FROM THE AEROELASTIC PREDICTION WORKSHOP

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Keywords: Computational benchmarking,Validation, HIRENASD, Benchmark Super-Critical Wing, Unsteady separated flow, Unsteady aerodynamics.

Abstract: The AIAA Aeroelastic Prediction Workshop (AePW) was held in April, 2012, bringing together communities of aeroelasticians, computational fluid dynamicists and experimentalists. The extended objective was to assess the state of the art in computational aeroelastic methods as practical tools for the prediction of static and dynamic aeroelastic phenomena. As a step in this process, workshop participants analyzed unsteady aerodynamic and weakly-coupled aeroelastic cases. Forced oscillation and unforced system experiments and computations have been compared for three configurations. Lessons learned regarding experimental, computational and comparison methods are discussed in this paper. Workshop participant opinions of recommended paths forward and workshop shortcomings were solicited and are discussed.

NOMENCLATURE

x/c	Chord-wise coordinate, normalized by local chord length

C_p	Coefficient of pressure
M	Mach number
q	Dynamic pressure
Re_c	Reynolds number based on chord
α	Angle of attack
ω, f	Frequency - radians/second, Hz
AePW	Aeroelastic Prediction Workshop
BSCW	Benchmark Supercritical Wing
CFD	Computational Fluid Dynamics
CRM	Common Research Model, associated with DPW
DPW	Drag Prediction Workshop
ETW	European Transonic Windtunnel
FRF	Frequency Response Function
HIRENASD	HIgh REynolds Number AeroStructural Dynamics
TDT	Transonic Dynamics Tunnel

1 INTRODUCTION

The AIAA Aeroelastic Prediction Workshop (AePW) was held April 21-22, 2012 in Honolulu, Hawaii, in association with the 53^{rd} AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, and sponsored by the AIAA Structural Dynamics Technical Committee. The AePW and its follow-on activities are collaborations within the aeroelastic community to assess the state-of-the-art in computational aeroelasticity, assess the experimental data available for performing this assessment and provide a roadmap forward [1–4]. The intention is that the roadmap will address the required developments in computational, experimental and comparison methods. The direct objective of the first workshop, assessing our ability to predict unsteady aerodynamic behavior in the transonic range, came about by considering the aeroelastic problem from the perspective of validation building blocks. The workshop approach was to perform computations on configurations, exercising an array of codes, and compare the computational results with each other and with existing experimental data sets.

The workshop kickoff was held at IFASD 2011, two years ago [1] and the workshop was held a little over a year ago. Continuing data comparisons and computational studies are ongoing to address and extend several aspects of the AePW work. The current paper represents an assessment as of the date of its writing. The objectives of this paper are to discuss the fundamental questions: What have we learned so far? What should we have done differently? What are the recommended benchmarking and research paths forward?

A lessons learned summary paper was presented at the 54th AIAA/ ASME/ ASCE/ AHS/ ASC Structures, Structural Dynamics and Materials Conference [3], held in April 2013. That paper included opinions that were expressed at the workshop and in subsequent communications. It also served as a starting point for soliciting wider viewpoints on the above questions. The current paper re-iterates the principle messages of the previous publication and extends the content to focus on the collected opinions, questions raised by those opinions and on suggested paths forward.

2 WORKSHOP FORMULATION & PARTICIPATION

The coarse-grain building blocks in aeroelasticity are: 1) unsteady aerodynamics; 2) structural dynamics; and 3) coupling between the fluid and the structure. The organizing committee members viewed the unsteady aerodynamics portion of the problem as the most challenging and the aspect that introduced the most uncertainty into an aeroelastic analysis. In the 2012 workshop, we chose to focus primarily on validating unsteady aerodynamic models and methods, with an initial venture into a weakly coupled aeroelastic system. Within unsteady aerodynamics, the choices of smaller building blocks to include in the first workshop were driven by several criteria. The first criterion applied is the existence of a compatible and sufficient experimental data set. The second criterion applied for the initial workshop effort was perceived simplicity, both of configuration and phenomena. The flow regime was the first decision that occupied the organizing committee. The subsonic flow was thought to be well-predicted by current methods, so the choice was made to focus on the more complicated transonic regime. The intent was to have a configuration that would exhibit transonic flow, but would not contain any regions that were massively separated.

Three configurations served as test cases for the AePW. Each are shown mounted in their wind tunnel test configurations in figure 1. The Rectangular Supercritical Wing (RSW) [5–7] was tested in the NASA Transonic Dynamics Tunnel (TDT) using Freon R-12 as the test medium. A summary of the AePW results for this configuration, experimental data, configuration details and additional reference material can be found in reference [8]. The Benchmark SuperCritical Wing (BSCW) [9, 10] was also tested in the TDT, using a similar heavy gas, R-134a as the test medium. Analyses of the experimental data set can be found in references [11, 12]. The High Reynolds Number Aero-Structural Dynamics (HIRENASD), led by Rheinisch-Westfaelische Technische Hochschule (RWTH) Aachen was tested in the European Transonic Windtunnel (ETW), with gaseous Nitrogen as the test medium. Wind tunnel model descriptions, testing and experimental data are reported in numerous publications including references [13–15]. Previous computational studies of HIRENASD include references [16–19]; computational results for the different configurations from several of the analysts participating in the AePW can be found in references [20–24].

The three configurations that were chosen for the AePW all had supercritical airfoils tested at transonic conditions. Each configuration was tested by actuating the model with a sinusoidal command. In the case of the RSW and BSCW, the actuation command was a pitching motion. For the HIRENASD configuration, the model was actuated using opposing sign forces applied to the top and bottom of the wing root, at the second bending mode frequency.

(a) RSW, mounted in TDT. (b) BSCW, mounted in TDT. (c) HIRENASD, mounted in ETW.

Figure 1: Test configurations, shown mounted in the wind tunnels.

For each configuration, unforced system (steady) and forced oscillation (unsteady) analyses were performed and compared with existing experimental data sets. The unforced systems for the different configurations were treated either as rigid (RSW, BSCW) or flexible (HIRENASD) and analyzed with corresponding methods, as shown in table 1. The forced systems were similarly treated, analyzed with time-accurate solutions for the unsteady flow fields. Assumed-rigid and aeroelastic systems were analyzed differently. Table 2 shows the test condition for the cases principally used in this paper for illustrating the lessons learned. Reference quantities for each geometry are detailed in reference [2] for each of the configurations.

Table 1: Solution processes for AePW configurations

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

† Performed only by analysis team HIRENASD-B [2]
‡ Performed by subset of analysis teams

3 WHAT HAVE WE LEARNED TO DATE?

Many of the following points will be illustrated in the presentation and discussion of the data sets shown in this paper. Details pertinent to other points, however, will require that you read the supporting references. The workshop effort utilized existing experimental data sets to validate or benchmark aspects of computational aeroelasticity tools. The workshop was structured to address the following questions.

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

Table 2: Primary test conditions and airfoil descriptions

Configuration	Mach	α, degs	Re_c, millions	Excit. freq, Hz	Red. freq, $\omega c/2V$	Airfoil
RSW (c_{ref} = 24 inches)	0.825	2	4.01	10	0.15	12% thick airfoil modified from an 11% thick design with design point Mach 0.8, CL 0.6
BSCW (c_{ref} = 16 inches)	0.85	5	4.49	10	0.09	SC(2)-0414
HIRENASD (c_{ref} = 0.3445 m)	0.8	1.5	7	80	0.39	BAC 3-11

development?

- Given the comparisons that we were able to make, what comparison data or experimental data characteristics would have improved our confidence in experiments representing relevant truth? Through the exercise of existing data sets, the workshop team also sought to identify requirements for additional validation experiments by further defining what constitutes a "good validation data set" for computational aeroelasticity.

The following questions are listed and answered to the best of our ability at this point. As analysis of the data sets continues, we hope to update this information, increasing its value for future efforts.

- What were the most challenging aspects regarding our chosen configurations? What were the consequences of these aspects?
  - Each of the principal test conditions for these configurations contained an oscillating upper surface shock, and in some cases a lower surface shock. The largest magnitude of the dynamics, i.e. in the Frequency Response Functions (FRFs), is the shock oscillation. For forced oscillation cases, the shock oscillation follows the forcing function and responds primarily at the same frequency for these reduced frequencies. [25]
  - The most challenging aspect of analyzing the RSW configuration was introduced by poor experiment set-up. The influences of the proximity of the model to the wind tunnel wall and the undersized splitter plate were not as fully understood when the model was originally tested as they are today. The consequence of attempting to capture the wall influences was that the CFD solutions varied widely, even for the unforced system results. We don't currently view the variation present in these results as an accurate assessment of the variation introduced by analysts' choice applicable to the state of the art. [8]

- Shock-induced separated flow and trailing edge separation was present for the BSCW configuration at our selected test conditions. Lower surface separation in the cusp region was also likely to have occurred. The computational methods that were applied had difficulty producing converged solutions for the unforced system and for the lower frequency forced oscillation case. We have attributed the convergence problems of these solutions with the complexity of the flow field and lack of appropriate fidelity in turbulence model. [12, 24]

- HIRENASD was not as challenging as the simpler geometries of the RSW and BSCW due to test condition selection and airfoil geometry. The resulting flow physics were more easily captured by the flow solvers chosen. The zero-lift case, chosen with the thought that the shock would be less stationary, offered less of a challenge to analysts than the test case with an upper surface shock. [25, 26]

- What have we learned about the state of the art in aeroelastic computations?

    - Using RANS, we were not able to accurately capture separated flow associated with the BSCW at the chosen test conditions. General discussion of separated flow modeling requirements can be found in reference [27] and recent work associated with the Drag Prediction Workshop (DPW) on this same general topic is found in reference [28]. Although the test conditions were thought to generate moderately separated flow, the region of separation appears to extend from the mid-chord (shock location) to the wing trailing edge. Further, the dynamics of the flow are of essential interest in our studies. While the RANS solutions may be able to predict an averaged influence of separation for small separation bubbles, they appear insufficient for either the unforced or forced oscillation responses of the BSCW configuration at Mach 0.85, $\alpha = 5°$. [12]

    - Distributed or local quantities (e.g. C_p) should be examined, rather than integrated quantities (e.g. lift coefficient) to determine solution accuracy, convergence with respect to grid and time step size and other properties of interest. An example of errors interacting and offsetting to disguise each other is shown in reference [26]. The Euler results consistently predicted the shock magnitude and location very differently than the RANS solutions, however, the integrated lift did not indicate that the Euler solution was an outlier. Other examples are given in literature associated with steady CFD calculations and experimental data by Tinoco [29].

    - Grid refinement was not shown to improve correlation with experimental data for any of the configurations. For HIRENASD, the grid refinement did, however, reduce the variation in the predictions. [26, 30]

    - Time step refinement was not systematically investigated by many analysts. In the few cases where it was examined and separated flow was present, qualitative changes in the results were observed.

    - Large variations were observed in both the unforced system response and the frequency response functions. There is an insufficient statistical sample size to assess the causes from among the possible sources. That is, not enough computational data sets were submitted with consistent parameters. Differences in grid, time step size, convergence level, turbulence model and other numerical specifications exist among the submitted results. [8]

  - Wind tunnel wall effects are, in general, ignored and configurations analyzed as if in free air.

- What have we learned regarding flow solvers?

  - The computational fluid dynamicists generally chose RANS flow solvers, and the majority chose to use either a Spalart-Allmaras turbulence model [31] or Menter's Shear Stress Transport turbulence model [32]. These choices reflect the state-of-the-art or perhaps, better-phrased, the state-of-the-current practices within the CFD community. In terms of common practice for aeroelastic solutions, this represents the practices of those on the leading edge of modeling complexity. This level of flow solution is perhaps becoming more common, however, linear methods such as doublet lattice aerodynamics [33] and ZONA [34] are still more commonly used by practitioners.

  - In cases without large separated flow regions or significant wind tunnel wall boundary layer effects, the RANS computational methods capture qualitative features for these fairly thick supercritical airfoils. [35] The scatter among the AePW results is large where viscous effects are significant. In the cases where separated flow or geometrically-thickened boundary layers are indicated by the experimental data, these methods appear to qualitatively mis-predict even the steady pressure distributions. This is thought to be due to the time-averaging introduced through the turbulence models employed in the RANS and URANS solvers. Even in a time-accurate simulation, if the time step is not small enough, or there are not enough subiterations, vorticity and separation features are smeared, and reattachment in particular is missed. [36] The HIRENASD compared better with experimental data than the other two configurations, attributable in part to the lack of separated flow on the HIRENASD. This qualitative difference in the flow field is assessed to be due to the less severe airfoil geometry, Mach number and angle of attack. [3]

  - Performing time-accurate solutions for unforced systems may be necessary. Paying attention to convergence of dynamic quantities with respect to time step size is recommended. [37] The time-accurate solutions using RANS, however, have led to consideration that higher fidelity flow solvers may be required to capture the aerodynamic source of the excitation. [24]

  - Flow solutions that offer better fidelity in capturing turbulence, such as LES or DES, have generally been recommended in the literature for analyzing cases where "massively separated flows" exist, usually occurring at high angles of attack. [27,38,39] The highest mean angle of attack case for the AePW was the BSCW configuration at $\alpha = 5°$. This test case generated what was assessed a priori as "moderately separated flow." From the perspective of inducing separated flow, this was considered to be a moderate angle of attack. However, the separated flow features are significant enough to cause a qualitative change to the shock motion and aft loading. [12] These changes are significant for integrated loads such as lift and pitching moment coefficient; they are likely also to be significant for assessing aeroelastic stability, which is highly dependent on phase relationships and load distribution. [40] The workshop results for BSCW led to the assessment that the URANS solutions may be inadequate for this case. [22, 24] Some analysts are pursuing higher fidelity methods for this configuration.

  - Initial studies have provided some understanding of the interdependence of the temporal discretization and the turbulence models of hybrid RANS/LES solutions. This issue should continue to be examined as further high-fidelity analyses are undertaken. [24]

  - In order to correctly compute the steady pressure distribution, it is important to assess the rigidity of the model and to obtain the correct deformed shape for flexible models such as the HIRENASD. Failure to do this results in effective changes in the local chordwise angle of attack. Using the rigid shape, rather than the deflected aeroelastic shape resulted in overprediction of the pressure distribution. [41] The impact on the forced oscillation results is discussed in [26].

  - Methodologies for performing oscillatory simulations are not standardized. Several methods were employed, although it has not been assessed whether the difference in oscillation method was a significant source of variations in the results. [2]

  - Analysis teams almost universally chose to build their own grids, leading to potential associated uncertainties and variations. Most analysts, when asked, simply said that it was easier for them to build their own grid rather than translating an existing grid for use with their own software. [2]

  - Convergence criteria and subiteration criteria are not uniformly applied. Each analyst chose their own best-practice criteria. [2, 20–24]

- What have we learned regarding experimental data?

  - "Steady," "static" and "stationary" are misnomers when applied to the experimental data, and also perhaps in the case of computational data. [42] The steady data was acquired from wind tunnel models that were sitting in the freestream turbulent wind tunnel flow field. These unforced systems generated data that contained oscillatory shock motion, oscillating regions of separated flow, influences of structural dynamic and facility aerodynamic modes. [12] "Static" computational solutions of the BSCW indicated the presence of an oscillating shock. [20–22, 24]

  - Using the mean value to capture a pressure distribution where there is an oscillatory shock results in smearing, canting and magnitude reduction of the pressures in the region of the shock. Mean value representations even for the unforced system should incorporate maximum and minimum bounds if nothing more descriptive. [12, 42]

  - A validation data set should contain repeat data points and small intentional variations of test parameters such as Mach, angle of attack and Reynolds number. [43]

  - An ideal data set would contain simultaneous measurements of time-dependent structural deformation, integrated loads, unsteady pressures, skin friction coefficients, and off-body flow fields.

  - Time-domain data for presumably steady tests should be acquired and saved. [12]

  - Wind tunnel wall boundary layer interactions may dominate a data set if the experiment is not carefully designed or conducted to avoid these effects. Measurement of facility boundary pressures and accelerations should be considered in any benchmarking test. [8]

  - A potential source of error in experimental set-up includes not just proximity of a model to the wall, but also testing with the wall slots open. This is not a direct lesson learned from the workshop, but one learned in the past that bears on interpreting errors in the data sets and design of future experiments. The wind tunnel walls of the TDT, ETW and most transonic wind tunnels have expansions slots to allow for transonic testing. For semi-span model testing, it is important that the wall near the support have the slots closed to reflect the symmetric boundary condition required for the model. During testing of the High Speed Research Rigid Semi-span Model (RSM) in the TDT, the wind tunnel wall slots were open at the support wall. Subsequent testing of the same model with the near-wall slots closed demonstrated a significant effect on the lift curve slope. [44] The RSM was a very large model, mounted directly on the wall, without the benefit of a splitter plate, increasing the significance of these effects. Both the RSW and the BSCW were tested with the wall slots open. The proximity to the wall and the undersized splitter plate makes the RSW data set more susceptible to the errors introduced by the open-slot effects. In the case of the BSCW, the open-slot effect cannot be ruled out as a potential source of error in the experimental data set.

- What have we learned regarding postprocessing of computational data?

  - Computational solutions were not run, typically, for a sufficient amount of time to utilize classical techniques for assessing and reducing the errors in the Fourier coefficients. This is not a fundamental limitation, but rather a choice made by the computational teams, either by oversight or due to computational expense. When the frequency of the response is not exactly known or not exactly captured in an integer number of data samples, this becomes important. For the HIRENASD case, sufficient time records were generated by several analysis teams to allow us to determine that for the HIRENASD cases, the responses were linear relative to the forcing function at the frequency of oscillation. Under those circumstances, a single cycle of response was sufficient to produce accurate FRFs. Without the other analyses, however, we would have had no statistical confidence in the FRF results. [30] For the BSCW case, the required record length is still under investigation. [24]

  – The data processing for CFD data is significantly different from classical experimental data processing. It is much more reminiscent of processing signals generated from a multisine signal. The results are highly sensitive to exactly capturing single cycles and setting Fourier analysis time record length to match. [30, 37, 45]

  – Classical Fourier analysis techniques may not be sufficient for analysis of CFD data that consists of limited sample sizes and short time records. New techniques that can be equally applied to both CFD and experimental data should be investigated.

  – Influences due to post-processing methods and approaches can be significant. A united processing method should be applied to all computational results. The software and personnel applying the methods should be the same if at all possible. [30]

  – The amount of data produced by a fine grid CFD solution can overwhelm both a post-processing analyst and the associated computer. Unifying the post-processing has benefits, but the data transfer and data reduction may require new processes.

- What did we learn about test case selection?

  – There were too many test cases in this workshop. The number of configurations-3- diluted the potential lessons learned for any single configuration, and made it exhausting for the analysis teams.

  – Have a benchmark test case. While choosing a challenging case is a good thing, choosing a first test condition for putting a "stake in the sand"* is essential. In mid-analysis cycle we added the Mach 0.7 case for the HIRENASD configuration. For those who had not previously analyzed the HIRENASD, this provided a good checkout case for their procedures and parameter selections. We should have done the same thing for the BSCW case. To rectify this, we are making an experimental data set at Mach 0.7 at a lower angle of attack available to analysts. This new benchmark case has transonic flow and oscillating shock, but does not contain separated flow. [12]

*The origin of this idiom is unclear from literary references. It is used here, however, to reflect several ideas. A stake is used to mark a boundary with authority. Here, the boundary is the difference between what is established and what is questionable. The stake marks the point at which we, as a technical community, have established knowledge to a specified degree of certainty. The "sand" aspect reflects the impermanance of the surrounding information. The transient nature of the boundary condition of the stake's driven end also cautions that a declaration of a benchmark in an evolving technical field should be made tentatively.

- What have we learned about conducting a workshop?
  - The scope of the workshop should be focused.
  - Overhead tasks or tasks for the common good need more support from more participants. These tasks include grid generation, preliminary computational checks and data reduction tasks.
  - Perform preliminary analyses on each case to identify major issues before general workshop participation begins.
  - Unify the post processing.
  - Clearly define the minimum (mandatory) calculations.
  - Lay out strict guidelines for participation and enforce them.
  - Administrative support could ease the overall workload and allow technical people to focus on the technical aspects.

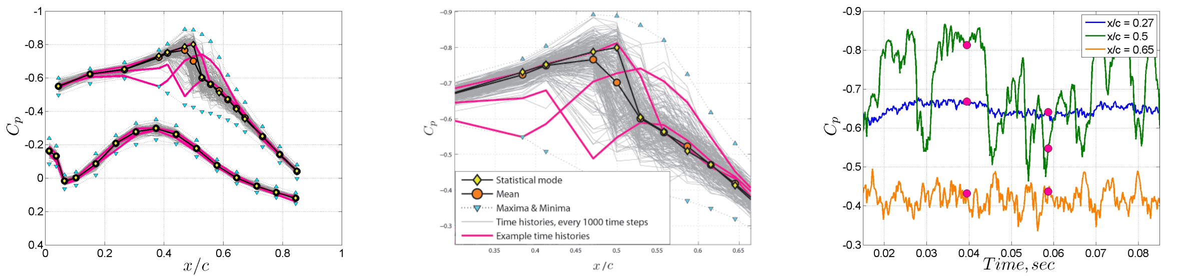
4 TECHNICAL DISCUSSIONS

4.1 Unsteady content of unforced system data sets

Several of the computational teams were concerned at the range of the experimental data for the cases that were supposed to have no forcing function. These data sets are the "steady" or "static" or "stationary" data cases and yet the bounds on the data are quite large, particularly near the upper surface shock. The statement was made, "The variability in the C_p data from the HIRENASD experiments seems excessive, especially when compared with other data used for CFD comparisons, such as data from the DPW and HiLPW. This variability seems very large considering the sophistication of the wind tunnels which are designed to produce repeatable and accurate drag numbers to within a few counts."

This is a point that continues to be a factor in characterizing unforced system data. The unforced system data contains dynamics including large changes in pressure coefficients on the upper surface as the shock moves. This issue was discussed relative to the BSCW data set at the AePW [12], but is also applicable for the HIRENASD [42]. Recent discussions among those involved in the HIRENASD testing and data reduction continue to explore improved methods of characterizing the data. There are two related issues: representing the expected distribution (usually characterized by a profile of mean values along the chord), and representing the variation about the expected value profile.

The current AePW data processing standard is to calculate the statistical mode as the first statistical moment in the vicinity of the shock, rather than the mean. In the current publication, we have principally displayed the mean values for consistency with previous publications. Alternatively, reference [46] employs a kernel density estimate method to represent the expected value of the system. The influence of these alternate characterizations of the first statistical moment of the data is to sharpen the shock (make it more



(a) Time histories and statistics (b) Focus on the upper surface shock region (c) Time histories of selected sensors

Figure 2: HIRENASD, experimental data of the unforced system, Station 4

vertical) and show it as stronger (larger difference between pressure coefficient ahead of and behind the shock) in comparison to the mean value representation. [12, 42] These alternate representations, though, do not capture the range of motion of the shock or the variation about the expected value profile.

The variation has been represented in several ways during the AePW data analysis process. Initially, Gaussian distribution statistics were used to represent the data. [25] Bounds of two standard deviations relative to the mean were displayed at the AePW in April 2012. In the year since, we have principally displayed bounds showing the data maxima and minima for each chord location. In some plots, the 99.5% and 0.5% capture bounds were used as bounds rather than the strict maxima and minima. Reference [12] shows details pertinent to the BSCW; reference [42] shows details pertinent to the HIRENASD. An example using HIRENASD data is shown in figure 2. Experimental data time history examples at span station 4 are shown as a function of chord location in figures 2(a) and 2(b) and as a function of time in figure 2(c). In figures 2(a) and 2(b), each of the grey lines represents a different point in time. Here, every 100^{th} time point is selected for plotting. The mean, mode, maximum and minimum profiles, computed using the entire time history are also shown. As the capture bounds are constricted to eliminate the more outlying values, the plotted bounds squeeze in and eliminate white space. [42] The three raspberry-colored lines in figures 2(a) and 2(b) are snapshots at specific times. Subsets of the time histories associated with sensors at three chord locations are plotted in figure 2(c). In this figure, the time points corresponding to the snapshots of the previous figures are identified by the raspberry-colored circles. These plots show that the bounds included in figures of unforced system data principally represent the dynamic content of the signals, rather than a variation of mean value.

The question of why the data sets for the AePW have so much variation in comparison to other published data sets for benchmarking workshops [47–50] is interesting and requires future consultations with those who generated and analyzed those data sets. The answer has several suspected contributors. Currently viewed as the most likely sources of this difference are the data processing and instrumentation. For the AePW data sets, the instrumentation and data acquisition systems were capable of measuring and recording data minimally at 1000 Hz. The time history records were saved and used to generate the bounds. In many of the similar workshop activities, time-averaged and spatially-integrated quantities are emphasized. Additional possible sources of the apparent differing variation levels of the data sets are 1) the models for this workshop are designed to be moved and thus the mounting mechanisms have some amount of freeplay in them; and 2) the excitation signals for all data sets examined have some small presence in the data, even for the unforced system cases.

4.2 Industry perspective on the use of CFD for flutter analyses

Rudy Yurkovich assembled his experiences and commentary on the status and importance of unsteady aerodynamic predictions for flutter in 2003. [51] His summary of the requirements for unsteady aerodynamic capabilities are that the codes must:

Be accurate in the transonic range;

Execute with sufficient speed;

Incorporate the influences of upwards of 100 structural dynamic modes; and

Handle non-linearities such as control surface freeplay.

Several of these points are reinforced by the current viewpoints expressed from industry partners in the AePW effort.

One of the most important aspects of commercial aircraft production flutter and loads analyses is the sheer number of cases which are required to be analyzed to certify a product. This may be in contrast to the perspective of researchers focused on advancing the state of the art. Production analysts want the right answer, but they need the answer now. A typical design iteration cycle (load cycle) may take approximately 3-6 months depending on complexity. During this time, models are prepared, input data generated, cases run, results reviewed and if necessary, reruns made. For a typical flutter analysis sequence during this typical loads cycle, the manufacturer looks at approximately 13-15 Mach numbers, 100 or more unique mass cases, 70 altitudes and 2 symmetry configurations. In round numbers this represents about 200,000 analysis points. With current linear frequency domain methods, which incorporate altitude variation directly into the solution process [52, 53], the number of solutions can be reduced by almost 2 orders of magnitude. This set of cases is then used to determine a smaller number of actual configurations where the aircraft is most flutter-critical. This subset is then used for parametric studies of flutter-sensitive inputs such as control surface hinge moments, stiffness and mass variations due to expected variations during the fleet production and service lifetimes and the many failures that can occur including structural and system. These additional parametric and failure cases can easily double the total number of cases to almost 500,000 unique cases. Current state-of-the-art linear methods utilize kernel function solutions to potential theory [33] and heuristic or CFD-based correction methods [54]. This methodology allows this task to be turned around in approximately 2-3 months. This lines up well with the aircraft design cycle iteration. Replacing this by an equivalent Navier-Stokes-based aeroelasticity capability extends each flutter point calculation time to approximately 1 day if we assume a high performance cluster and a reasonable number of processors per analysis. The analyses for the single design cycle would take approximately 500 years. Making the reasonable assumption that the higher fidelity computational methods are not needed for all cases, but perhaps maybe the most challenging 1% of all the cases, this still leads to 5 years for one design cycle. The needs of industry with regard to high fidelity computational aeroelastic simulations focus on predicting flutter for those cases that cannot be predicted using linear aerodynamics and then the ability to use that data to generate good/conservative analyses using corrected linear methods or some similar fast method.

4.3 Nonlinear phenomena from an industry perspective

Buffet is a very difficult phenomenon to predict; the aircraft industry is none-the-less asked to provide criteria and requirements to cover buffet all the time. [55] For small items (small antennae etc.), this may not be a large task but for items such as flaps and other control surfaces, this can provide sizing loads, or in the very least, life-limiting requirements. The ability to reliably predict buffet phenomena cannot be understated, as the current practice is to make a conservative –heavy– assumption, followed by a validation of the assumptions' conservatism in flight test. Flight testing is both expensive and late in the process, creating technical and economic problems.

Freeplay can be cast in a similar vein. Current requirements [56, 57] point to expensive flight testing with end-of-life wear duplicated on critical components, in high risk aeroelastic stability tests. Having a reliable or even modestly conservative approach to a validated freeplay analysis capability would be a tremendous economic and schedule relief in aircraft design.

5 EXPERIENCES FROM EACH CONFIGURATION

The three AePW configurations are discussed individually in the following sections. Observations pertinent to each configuration are made, based principally on the data presented in the references.

5.1 Rectangular Supercritical Wing

The RSW configuration was chosen as the nominally simplest test case, however, this was determined not to be the situation. The geometry of the RSW is a rectangular planform and the structure was considered to be rigid, particularly because the excitation frequencies chosen were well-below the measured structural dynamic frequencies. The complications of this configuration originate with the mounting of the model in the wind tunnel. The experimental data was obtained using an undersized splitter plate with an insufficient stand-off from the wind tunnel wall and sidewall slots open. During the AePW effort, the tunnel wall boundary layer influence on the RSW was investigated and shown to extend over a substantial portion of the wing span. The inboard row of pressure sensors, located at 31% span, was strongly influenced by the interaction with the wind tunnel wall boundary layer. The second row of pressure transducers on the wing, located at 59% span, was also shown to be significantly influenced by the tunnel wall.

In generating the computational grids, the domain was modified from the original gridding guidelines to expediently simulate the influence of the wind tunnel wall boundary layer on the wing pressure distributions. This was done by including a flat plate representation of the wind tunnel wall, modeled as a viscous surface, and subsequently tuning the upstream computational domain extent. Wind tunnel calibration data was used to determine the computational domain that produced the equivalent wind tunnel wall boundary layer thickness at the wing location. The modeling of the wind tunnel wall as a viscous surface and the change to the computational domain extent had the effect of shifting the shock forward. Reference 3 presents details of the studies that were conducted in developing this approach.

Inconsistencies introduced in resolving the wind tunnel wall issue resulted in increased scatter in the RSW computational results. This process also resulted in the specifications for the computations becoming unclear. The primary data set that was requested was the pressure distribution. Integrated loads were treated as more of an afterthought and inconsistent definitions of the integration area and normalization constants developed.

Reference [8] is intended to be a final report for the RSW data set. There is no detailed experimental data to interrogate, no wind tunnel model to examine or retest. Analysis-only comparisons were discussed as a possible follow-on activity. Going forward, however, interests have shifted to analyzing the BSCW at simpler test conditions as the benchmarking point since experimental time history data and a model that can be retested are both available for this case.

5.2 Benchmark SuperCritical Wing

Many of the computational teams had difficulty achieving a converged solution for this configuration at the AePW analysis condition, even for the unforced system case. [2, 25] The challenges of analyzing the BSCW model stem from the flow physics at the AePW test condition.

Prior to the workshop, little emphasis had been given to the details of determining solution convergence. [1] This was one area where recommendations for improved analyses were made. In addition, the AePW analysts were given no guidelines as to whether unforced cases should be run as time-accurate or steady-state simulations. The intent was to let the physical characteristics of the problem and the observations of the individual analysts determine their simulation strategies. The chosen BSCW test cases included separated flow even under unforced conditions. [12] All of the AePW analysts attempted steady simulations of the case with varying degrees of success. Some noted a lack of convergence in the steady simulation, but did not perform a time-accurate simulation of the unforced system, assuming that the poor convergence would be resolved in the initial transient of the subsequent forced-oscillation simulation. At least one analysis team performed a time-accurate simulation of the unforced case and demonstrated that the case produces a non-decaying unsteady separated flow character.

The experimental data, examined in detail in reference [12], is shown to contain dynamic information for the unforced system case. Some of the dynamics appear to originate as aerodynamic modes related to the separated flow over the aft portion of the airfoil. In reference [12], it was determined that there are important qualitative changes introduced by the separation. Additionally, severe nonlinearities were shown to exist with respect to excitation amplitude. These physical traits suggest that performing time-accurate solutions using higher fidelity turbulence models should be employed for this configuration as in reference [24].

Another possibility is that, although the splitter plate is large and well-offset, there could be significant viscous interactions with the splitter plate boundary layer. Wind tunnel testing of the isolated splitter plate is reported in reference [58]. One computational team has performed an initial investigation of this issue [21]. A future computational study, using wind tunnel data from testing the splitter plate alone for comparison is recommended. As pointed out in reference [58], the splitter plate used for the BSCW test reduces the Mach range capabilities of the TDT. The AePW test condition is at the limit of the Mach range where reference [58] shows reliable unsteady pressure measurements.

5.3 HIgh REynolds Number Aero-Structural Dynamics model

The HIRENASD and associated configurations are well-documented in published literature. [13–15] The HIRENASD data sets examined for AePW do not contain a shock strong enough to induce flow separation, as calculated in reference [3] using isentropic flow relationships. [59] The strongest shock case is used for illustration in this paper. The HIRENASD was chosen for the workshop as a first foray into aeroelastic systems; the important aeroelastic consideration to capture for the HIRENASD was found to be the static aeroelastic shape. Neither modal coupling nor excitation amplitude nonlinearities were found to be significant in the frequency response function computations at the excitation frequencies. [41] Computational and experimental data were in better agreement for the HIRENASD configuration than for the simpler planforms. [25] This better agreement is attributed to test conditions. Two test conditions at Mach 0.8 were examined during the workshop: $\alpha = 1.5°$ at $7 * 10^6 Re_c$ and $\alpha = -1.34°$ at $23 * 10^6 Re_c$. The example HIRENASD plots shown in this paper correspond to the first condition- it was more popular among the analysts and exhibited more dramatic behavior. Detailed presentation of the HIRENASD data and comparisons are the subjects of references [26, 30, 42, 60].

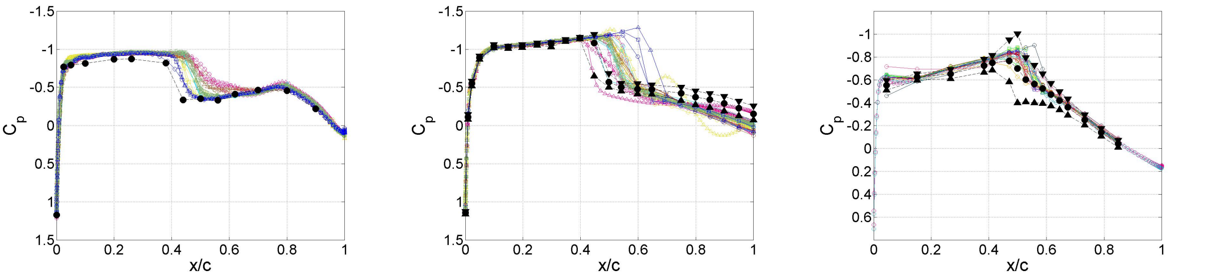
6 DATA REVIEW

The data sets that are shown in this paper are a small subset of the available comparison data sets. Side-by-side comparisons of the results for the three configurations near the 60% span are presented in reference [3]. Similarities and differences are discussed in the reference and summarized here. Comparison plots are shown in figures 3, 4, 6, 7 and 8. Each plot shows computational results by colored symbols and lines. Experimental data is shown by filled black symbols. The mean (RSW, HIRENASD) or statistical mode (BSCW) profiles are shown by filled black circles; maxima and minima profiles are shown by filled black triangles. The data to be presented are unforced system pressure distributions and forced oscillation Frequency Response Functions (FRFs).

6.1 Unforced system pressure distributions

The dominant characteristic of the pressure coefficient distributions is an upper surface shock, as shown for each of the three configurations in figure 3. The lower surfaces also exhibit shocks or steep pressure gradients ahead of the cusp regions that characterize supercritical airfoil geometries. Inboard span stations exhibit stronger shocks than outboard span stations, shown for the RSW in reference [8] and the HIRENASD in reference [42]. The BSCW was only instrumented at one span station.

For all configurations, the computational results agree better with the experimental data sets near the mid-spans. [25] In the mid-span region, the experimental results are relatively unaffected by the aerodynamic influences of the wind tunnel wall boundary layers and



(a) RSW, station 2, 59% span ($\alpha = 2°$, M=0.825).

(b) BSCW, 60% span ($\alpha = 5°$, M=0.85).

(c) HIRENASD, station 4, 59% span ($\alpha = 1.5°$, M=0.80).

Figure 3: Upper surface pressure coefficient distributions, unforced system data (Black: experiment mean or mode, maxima and minima; Colors: Computational mean values).

they don't contain the more complicated flow structures associated with the vortices at the wing tips. The shapes of the pressure distributions are different for the configurations, but are consistent with historical and published data for these airfoil geometries and test conditions. [61, 62]

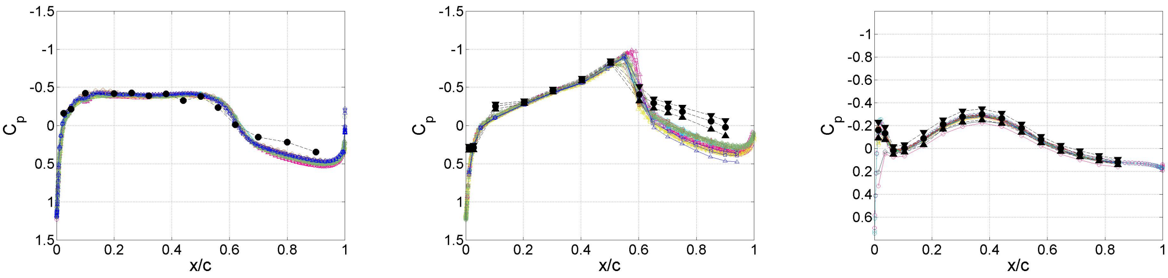
The shape of the upper surface pressure distribution differs greatly when comparing the three configurations. The forward portion of the distributions of the RSW and BSCW appear much flatter than the HIRENASD distribution and the upper surface shock is stronger for the first two configurations in comparison with the HIRENASD. These differences reflect the differences in the test conditions and geometry. The Mach number is lower for the HIRENASD, as is the angle of attack. Additionally, the HIRENASD is a swept wing, which lowers the Mach number normal to the shock. Finally, the airfoil geometry is substantially different.

The data sets were evaluated for flow separation using isentropic relationships [59] and historical guidelines [63]. While the RSW and HIRENASD data sets indicate attached flow at the conditions studied, the BSCW appears to have separation from the foot of the upper surface shock extending to the trailing edge.

The computational results show the upper surface shock predicted too far aft for the RSW and BSCW as illustrated in figures 3(a) and 3(b). The shock shape and distribution at the foot of the shock is poorly predicted for both configuraitons. Furthermore, the variation in shock location and strength shown among the computational results is large. Towards the trailing edge, the RSW pressure distribution shape is well-predicted. The BSCW, by contrast, is not. The negative pressure coefficient at the trailing edge is discussed in reference [12] as corresponding to separated flow. The computational results do not capture this behavior. [25]

For HIRENASD, the computations predict a shock location that is aft of the mean experimental pressure distribution as illustrated in figure 3(c). The experimental data bounds encompass all but one of the computational data sets, that set being generated with an Euler solution. [23] The computation results generally capture the shape of the pressure distribution. Additional work has progressed to examine influences of analysts' selections of parameters [60] and variations introduced by different grids. [30]

The lower surfaces also contain shocks or at least large pressure gradients near the leading



(a) RSW, station 2, 59% span ($\alpha = 2°$, M=0.825).

(b) BSCW, 60% span ($\alpha = 5°$, M=0.85).

(c) HIRENASD, station 4, 59% span ($\alpha = 1.5°$, M=0.80).

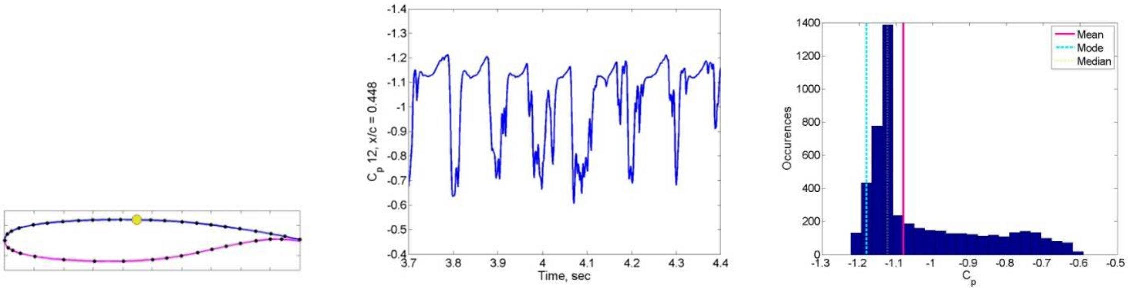
Figure 4: Lower surface pressure coefficient distributions, unforced system data (Black: experiment mean or mode, maxima and minima; Colors: Computational mean values).

edge of the cusp regions for each of the configurations. Harris [61] reported than supersonic flow on the lower surface of supercritical airfoils generally resulted in separation being observed in the cusp region. The current interpretation of the AePW data is that this holds true for the BSCW, possibly for the RSW, not for HIRENASD. On the lower surfaces, the computational results agree well with the experimental data with a few exceptions, most noticeably in the cusp regions of the RSW and BSCW as illustrated in figure 4. Overprediction of the pressure coefficients in the cusp region is more dramatically observed for the BSCW configuration. The pressure coefficient change across the cusp region is much larger for the BSCW than for the other two configurations. For the HIRENASD, the lower surface pressure distribution is well-predicted. The improved agreement between the experiment and computational results in the cusp region is thought to be due to the different flow physics. This experimental data set has a concave shape over the cusp region, indicating that the flow here is attached. Both geometry and test condition likely contribute to this qualitative difference and improved agreement. The cusp geometry of the HIRENASD airfoil section is milder than that of the other configurations, that is, the derivative of the shape change with respect to wing chord is smaller. The HIRENASD test case is at a lower Mach number and lower angle of attack than the other configurations. The Reynolds number for the HIRENASD case is higher, approximately 1-1/2 times that of the BSCW. All of these factors are such that they would tend to make the boundary layer more prone to remaining attached.

6.2 Forced oscillation data

Time history data was available to analyze for the BSCW and HIRENASD configurations. The forced system data sets all indicate that there are nonlinearities in the pressure responses as the shock oscillates across a transducer. The data sets show increased random components in the measurements in separated flow regions. An example time history and histogram is shown for the BSCW configuration, in figure 5, for a sensor being crossed by the oscillating shock. The extreme left skewness in figure 5(c) indicates that the shock spends most of its time behind the transducer, a feature that can also be readily confirmed by the pressure coefficient time history.

Frequency response functions [64] are calculated as the frequency-domain relationship between the pressure coefficients and a displacement measurement at the frequency of forced excitation. In the RSW and BSCW cases, the displacements used are the angles



(a) Transducer location (b) Time history (c) Histogram

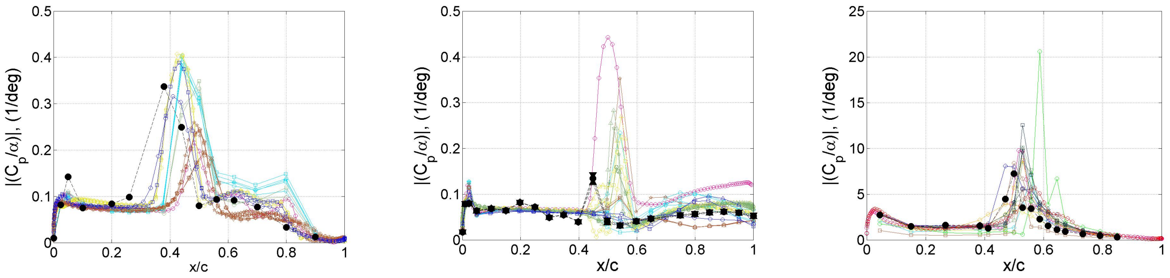
Figure 5: BSCW experimental pressure coefficient behavior for forced oscillation at 10 Hz, Upper surface pressure transducer 12, $x/c = 0.45$, in the region of shock oscillation ($\alpha = 5°$, M=0.85, 200 psf dynamic pressure).

of attack. For the HIRENASD, the displacement is the non-dimensionalized vertical displacement at a location near the wing tip. The FRF results shown in the current paper correspond to forced oscillation cases at frequencies and reduced frequencies shown in table 2.

Just as the unforced system responses were dominated by the upper surface shock, so are the FRFs. This is shown by large peak magnitudes, near the mid-chord for the example cases shown in figure 6. Considering all workshop results as a single group, the computational results predict the peak further aft than observed in each experimental data set. This is a reflection of the unforced system shock location prediction being too far aft. The FRF peak captures the motion of the shock as it follows the forcing displacement, responding principally at the forcing frequency.

Examining all of the FRFs as a group, the RSW is the worst-predicted case aft of the shock. The mismatch is possibly another aspect of the wind tunnel wall effects. Another possible source is the mismatch in the onset of locally separated flow as the angle of attack sinusoidally increases and decreases.

The BSCW shock dynamics are more poorly predicted than the other configurations. A relatively good match is shown between experiment and computations in the separated flow area in terms of the shape of the distribution, although the computations overpredict the magnitude. There are several points that should be kept in mind in interpreting these results. In this region, reference [12] shows that the coherence functions between the pressure coefficients and the angle of attack decrease, indicating that the frequency response function calculations contain more uncertainty in this region than in the forward area of the airfoil. It was also shown that the influence of the separated flow was not concentrated at the excitation frequency; it is either a broad-band excitation or concentrated at frequencies corresponding to aerodynamic modes. The time histories and frequency domain analyses presented in reference [24] show the increase in dynamics at non-excitation frequencies that are only captured in this FRF analysis as spectral leakage effects [64,65]. Spectral leakage effects are errors in the Fourier coefficients that occur, in this case, for frequencies in the vicinity of the frequency present in the signal being analyzed. One of the underlying assumptions in applying the Fourier transform is that complete cycles at the frequencies being analyzed are present in the time record. When there is a mismatch between the signal's frequency content and the Fourier frequencies, complete cycles are



(a) RSW, station 2, 59% span ($\alpha = 2°$, M=0.825).

(b) BSCW, 60% span ($\alpha = 5°$, M=0.85).

(c) HIRENASD, station 4, 59% span ($\alpha = 1.5°$, M=0.80).

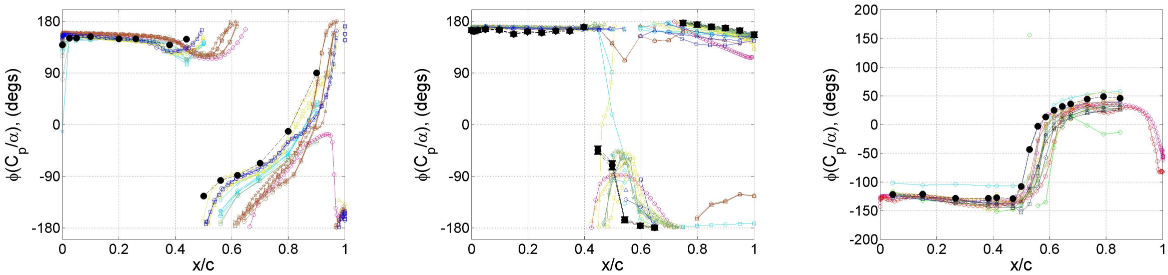
Figure 6: Frequency response function magnitude, Upper surface pressure coefficient distributions due to displacement, forced excitation data (Black: experiment; Colors: computations).

not fit by the Fourier analysis window and leakage errors occur.

For the HIRENASD, the peak of the FRF spans several of the chord-wise sensors. The shape of the peak indicates that the shock is crossing one sensor, but the sensor just aft of that point also contains considerable dynamics in comparison with the RSW and BSCW. This could be due to an expanded range of the shock oscillation, better sensor locations than available for the other configurations, or dynamic separation at the foot of the shock.

The phase characteristics, shown in figure 7, indicate the different character of each of the forced oscillation cases. The BSCW case was oscillated at a frequency that can be treated as nearly quasi-static; the reduced frequency for the case shown is 0.090. The results presented in the current paper are not the lowest reduced frequency case; the BSCW was also tested and analyzed at a reduced frequency of 0.009. The reduced frequencies for the cases in this paper are listed in table 2; the reduced frequencies for all cases examined in the AePW are shown in reference [2], tables 4, 5, and 6. The phase of the BSCW response is shown in the figure 7(b) to principally lie near 180°, which means that the pressure coefficient and the angle of attack differ by a sign. The phase at the shock location changes, almost to 0°, which represents in-phase behavior (i.e. both variables track together in time and have the same sign). Thus, the phase plot indicates that the shock is moving forward as the angle of attack increases. Despite the poor predictions of the unforced system pressure coefficient distribution in the region of separated flow discussed earlier, the computations appear to capture the sign of the shock motion correctly. This is significant because the shock motion phase changes with the onset of separated flow, as discussed in reference [12]. These two aspects of the computational results seem contradictory and bear further investigation.

In the lower surface FRFs, figure 8, the most notable discrepancies between experiment and computations are again found for the BSCW case. A shock is seen in all computational results near 60% chord, near the leading edge of the lower surface cusp. The experimental data shown in the figure does not indicate lower surface shock dynamics. However, examination of the experimental data at adjacent test conditions and the unforced system data indicates that the principal cause of the qualitative mismatch is that the shock motion occurs between the sensors at 50 and 60% chord. [12] The lower surface shock dynamics are thus missed due to the sparseness of lower surface sensors. For the other configurations, the lower surface FRFs are well-predicted and generate no surprises. [25]

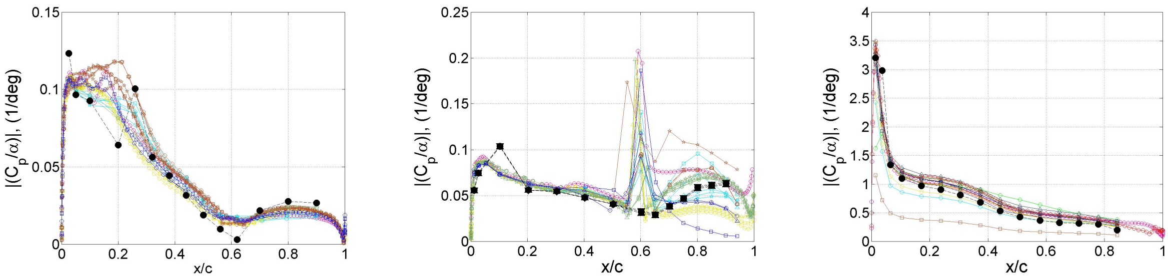


(a) RSW, station 2, 59% span ($\alpha = 2°$, M=0.825).

(b) BSCW, 60% span ($\alpha = 5°$, M=0.85).

(c) HIRENASD, station 4, 59% span ($\alpha = 1.5°$, M=0.80).

Figure 7: Frequency response function phase, Upper surface pressure coefficient distributions due to displacement, forced excitation data (Black: experiment; Colors: computations).



(a) RSW, station 2, 59% span ($\alpha = 2°$, M=0.825).

(b) BSCW, 60% span ($\alpha = 5°$, M=0.85).

(c) HIRENASD, station 4, 59% span ($\alpha = 1.5°$, M=0.80).

Figure 8: Frequency response function magnitude, Lower surface pressure coefficient distributions due to displacement, forced excitation data (Black: experiment; Colors: computations).

7 RECOMMENDATIONS & PATH FORWARD

With the AePW behind us, we turn to trying to define the path forward, based on the data, the findings and the experience. The following two sections of this paper document recommendations that have come from many sources, including feedback at the workshop itself, feedback provided at special conference sessions, and from the coauthors of this paper. The recommendations are not necessarily aligned with each other. There are three categories of recommendations provided here: configurations, technical aspects and logistical aspects.

7.1 Configurations

The common research model (CRM) that was used for the DPW provides a nice configuration for industry-pertinent configuration calculations. Useful modifications of the model could include features such as winglet designs, raked tips, and order-of-magnitude scaled structural dynamics. There would be interest in having a control surface oscillation also.

Modular configurations might allow interaction with other projects that are better funded. Current projects could be consulted to determine potential collaborations.

There are several existing data sets that belong to private companies or government agencies that might be substantially superior to those used for the AePW. These organizations could be approached regarding the possibility of releasing their data sets and geometry details sufficient for performing the matching computational studies.

A mounting and excitation system like the one used for the HIRENASD provides data that is essential for comparison of aeroelastic simulations. Future benchmarking experiments should attempt to use this type of system.

There are additional data sets available for both the BSCW and the HIRENASD test cases. Experimental data for additional cases for both of these configurations can be made available. For the BSCW, there are three test cases being examined that provide less complex and more complex flow fields: a low-Mach case without a shock, an attached flow case with a shock, and an alternating attaching and separating oscillation case. For the HIRENASD, it is proposed that the Mach number be varied: Mach 0.8, 0.85 and 0.88, at a high Reynolds number and varying the dynamic pressure. Examination of excitation of the other modes is a recommended extension. The second bending mode was selected for the AePW because it was viewed as the easiest case with the cleanest data. That is, the responses observed in the experiment contained information at the second bending mode frequency without significant influence of the other modes or the wind tunnel aerodynamic modes.

7.2 Technical

The path forward should involve detailed investigation of some areas that were not well-covered in the AePW, were completely neglected, or evolved as a result of the workshop.

In data reduction, examining the integrated sectional data would lend insight into the aeroelastic characteristics, much more so than the distributed quantities. This is a usual practice with high-aspect ratio wings, particularly for simplified aeroelastic analysis.

Eliminate the wind tunnel effects. The industry and military perspective is that matching flight test data is the desired outcome, not matching wind tunnel test data unless a detailed method is defined and validated for correcting to free-air flight.

Determine the requirements for sufficient computational solution time, relative to the data reduction methods employed, and make recommendations to the computational community. Clearly show the detriment of falling short of the specified recommendation.

Define metrics in terms of time required to perform an analysis, for example 4-5 hours to perform a flutter analysis. From this perspective, examine what code, computing resources and validation effort would be required to achieve this, given the current state of the art.

Computing resources is one area that has continued to "fall through the cracks"[†] of the AePW effort. Although discussed throughout the workshop preparation, this issue was not addressed in the final data submittals and comparisons. This issue is considered important, as we move towards more rapid analyses and wish to demonstrate the feasibility of performing higher fidelity solutions.

In future benchmarking activities, address the question of "what is the minimum analysis that can reliably produce the final product?" This will require that linear analyses be performed on the same configurations as the higher fidelity simulations. Are there simplifications of the higher fidelity simulations that can be successfully exercised to address large regions of the test conditions? Suggestions include linearized URANS/Euler, Euler, spectral methods and reduced order models of various types.

Illustrate the unsteady nature of experimental data sets. Determine best representation of the pressure distributions for CFD solutions to be compared against.

Extended studies of the BSCW are underweigh[‡] using hybrid RANS/LES solutions. [24] Initial results show favorable changes in the pressure responses, however, continuing discrepancies include dynamic content and shock location. Issues that should be explored using the existing experimental data sets include wind tunnel turbulence spectrum and structural dynamic participation of the wind tunnel model and splitter plate. The existing experimental data should be interrogated to learn as much as possible regarding requirements for time step specification.

Unify the post processing. Post-workshop analyses have demonstrated numerous issues that result in significant differences which have nothing to do with the quality of the numerical simulations. Utilize the same person and same software to examine all data sets and produce the final comparison data sets. The common grid study of the HIRENASD that followed the AePW highlights some of the effects that can significantly change the comparison data produced from a given CFD result. The post-processing in the common grid study was performed for all computations using the same processing and same person performing each of the post processing steps for all data sets. Those data sets in particular showed the errors introduced by different methods employed to extract the pressures alone the span-wise cuts. The cutting-plane point distribution and interpolation

[†]inadvertantly ignored; to be left undone because it has escaped a sufficient amount of attention. The earliest appearance of this phrase in literature post-dates the Canterbury Tales [66].

[‡]having raised anchor and sail, headed towards a harbor or goal

methods were demonstrated to influence FRF computations. An example FRF was produced by an analysis team for the AePW. The same analysis team re-analyzed their data with a presumed-identical post-processing method and obtained a different FRF. The unified processing for the common grid study produced still another FRF. The differences, particularly in the area of the shock, were substantial and are detailed in [30].

7.3 Logistical

Future workshops should have a more defined goal, specifying which aerodynamic or aeroelastic phenomenon should be modeled. Steps to performing those analyses should be specified rather than left to the computational teams to determine.

The computational teams were divided with regard to whether more workshops or fewer workshops were a good thing. It was suggested that an annual workshop was a good approach, with a tighter focus. The annual workshop suggestion made another computational team leader weep.

The workshop has a wealth of data for informing future analysis models, experimental models and criteria for assessing them. Developing guidelines from the information should be a part of a near-term future effort.

We should endeavor to bring high-performance computing to the project and find mechanisms for funding individuals to analyze and develop methods pertinent to this area.

8 OPINIONS & PHILOSOPHICAL DISCUSSION

Hindsight will hopefully give us foresight. An opinion expressed by almost all who responded to the call for opinions and lessons learned is that the problems of the RSW experiment data and analysis process should have led us to abandon this configuration and replace it with a low Mach number, angle of attack case from the BSCW data sets.

There are many issues that generated conflicting opinions among those who participated in the workshop. The differences reflect the perspectives from different organizations and what they would hope to achieve from a workshop. The continuing areas of differing perspectives are: configurations, complexity of flow phenomena and access to experimental data. Opinions were also offered and questions were raised regarding who participated in the workshop and what would motivate someone to contribute to this type of activity. The conflicting topics are discussed first.

In considering which configuration an individual or an organization preferred, there are several issues. The acknowledged issues are the degree of wind tunnel wall interference, the computational resources required, the airplane-ness, the adaptability for future testing, the complexity of the flow field, and the quality and quantity of the experimental data set.

Every configuration received low marks from at least one organization because it was viewed as containing wind tunnel wall effects. From computational teams that had analyzed a given configuration, however, only the RSW received low marks for this issue. One BSCW analysis team observed significant influences of the wind tunnel wall, which appear to exceed those measured in the published splitter plate calibration study. Several

HIRENASD analysis teams pointed out at least small recirculation regions near the wall and fuselage in their computational results. No one analyzing the latter two configurations thought that the issue was sufficient to warrant abandoning either configuration, however.

The configuration conflict goes beyond the perception of the wind tunnel wall effects. Several university and small business participants mentioned that computational resources are a significant issue in their configuration preference. While the RSW and BSCW are simple geometries, treated as rigid, the HIRENASD is a more complex geometry, treated as an aeroelastic system. The amount of computational resources to analyze the first two configurations makes them better-suited for those who have fewer resources. Another driver of the differing opinions appears to be that the HIRENASD resembles an airplane and has possible extension to more aircraft-like problems. Yet another driver is the superior suite of instrumentation that was used on the HIRENASD. This configuration originally offered the hope of having even more measurements for benchmarking against, and there is the hope that later tests would reclaim those capabilities. Specifically, measuring displacements and balance (integrated) loads. The excitation system can excite the model at any of the modal frequencies and combinations of frequencies, offering experimental data for more than a single mode.

With regard to differences in the flow field complexity that should be addressed, a conflict of opinions also exists. This issue partially drives the configuration conflict.

> "We should focus on unsteady separated flow in the transonic region."
> "It is premature to try and benchmark separated flow."

For those who are trying to define the leading edge of unsteady aerodynamic and aeroelastic analysis, the separated flow cases of the BSCW offer them an applicable configuration with geometric simplicity. For those interested in flutter solutions at cruise conditions, or quantifying the expected error or risk level associated with CFD solutions, the HIRENASD offers them an applicable configuration. This is also a resource issue. With the time and money available, which problem represents your greatest need? Maybe the biggest advantage of using space and time resolved CFD is the possibility to understand the flow characteristics in detail.

The final issue that appears to be a source of direct disagreement is whether or not experimental data should be available to computational teams. Acceptance of relying on CFD in a predictive manner will require that methods be demonstrated using blind test cases. The opposite viewpoint, though, is that if we are trying to push the envelope and use higher-fidelity methods, those applications need to be guided with experimental data. The requirements for gridding, time step size and other parameter tuning are not in the same category as flows that can be solved with established and tuned RANS turbulence models. This issue appears to be principally tied to the issue of complexity of the flow phenomena.

"This workshop participants did not include many methodology developers or code developers from the CFD community." This statement was made by one of the computational team leads. There are several interesting aspects of this statement to consider. How important is it? How much of the variation observed in the results is due to lack of skill and experience on the part of the computational teams? i.e. did this affect the quality in addition to the quantity of the solutions provided? Why was there a shortage of participation from developers in the CFD community? Only the last question is addressed, and it is addressed only through speculation and informal survey: lack of time; lack of funding; too many ongoing benchmarking activities; lack of importance of the problems being studied; insufficient information distribution; view that the problems being studied are not in their field; lack of knowledge on how to treat the problems; view that the test cases were not properly formulated; view that the test cases were too simple; view that the test cases were too complex; view that the test cases were unimportant; view that the experimental data sets were insufficient; view that the components of the analytical modeling being provided were insufficient; the scope of the workshop was too broad.

The above opinion ties in nicely with a question raised by another respondent to the request for opinions. What do they, as a company, get out of participating? Other than the data, which has been made available to everyone, regardless of participation in submitting their results, what is the benefit to an organization of submitting their best results? This is a question that necessarily has a different answer for each participant. The question needs to be asked of several groups. One group would be those who participated most actively in the workshop. Another group would be those who participated in other similar workshop efforts. Why did you participate? How did your organization benefit from participating? These are questions, located in the philosophical discussion section of the paper. Did you expect answers here?

9 SOME GENERAL CRITIQUES

Among the issues raised, there are some that seem to be small issues, but listing them and some potential underlying sources may produce useful actions and attitudes for future workshop efforts.

Among the reviews of the workshop was the criticism that the objective of the workshop was too broad. Some found it daunting and some found it too ambiguous to determine where to begin the computations. Assessing the state of the art in computational aeroelasticity or even unsteady aerodynamic modeling left the playing field too wide. This was illustrated by the way that the goals associated with each of the configurations diverged from each other. For the RSW, it became a wind tunnel wall modeling study, for the BSCW, it became a separated flow modeling exercise, and for HIRENASD, it became a variation assessment.

Participation was limited for some interested parties due to the volunteer nature of the workshop.

The workshop needs to be more militant regarding the use of grids, turbulence models and other variations. There should be a minimum set of common analyses (same conditions, grid, and turbulence models) for comparison. The minimum requirements need to be enforced and all other analyses posed as optional extensions that can be exercised.

The website isn't sufficient. The website isn't maintained to my liking. The website is confusing. The grids had problems. There were some sliver cells that caused our codes problems. The structural dynamics model needs additional tuning. We need more details from the experimental testbed. We need more information from the experimental testbed. The data formatting is inconvenient. The data formatting was not consistently supplied by computational teams. The organizing, collating, and checking of the data was a large task that was made more difficult due to inconsistent application of the formatting guidelines.

Many of these issues can find ready source in three categories: too small a workforce, lack of communication and the issues that naturally arise when using a historical database rather than a purposed experiment. Just as the computational teams were volunteer efforts, so were those performing overhead functions: generating grids, checking the grids, setting up and maintaining the website, preparing the experimental data sets, performing the data comparisons, combining the computational data sets into a database, addressing issues as they arose from computational teams, etc. One aspect of the workshop that seems to have been poorly handled is soliciting enough volunteers to handle these types of jobs and reasonably spread the workload. It should be noted that there were volunteers to handle some tasks that had to withdraw from those commitments, most notably in the area of grid generation. Informal survey of other workshop activities indicates that this problem is not unique to the AePW.

Some issues that were raised could not be addressed as fully as desired due to time constraints. Some issues could not be addressed as fully as desired due to unavailability of information, particularly when it came to experimental data. More frustrating for all concerned, however, was not being able to address issues because they weren't raised. A seeming benefit of working as a group is the ability to communicate an issue and resolve it in the most time-effective manner or simply pool[§] efforts to resolve it. One issue in improving communication with regard to technical challenges appears to be that individuals are reluctant to share their bad results. Without degrees in psychology, the authors defer to professionals of other fields to address the underlying causes.

10 CONCLUDING REMARKS

The findings from the Aeroelastic Prediction Workshop have been enumerated and the reader has hopefully been sufficiently directed to more details in the appropriate references. This document has attempted to capture the viewpoints that have been expressed regarding improving future workshop efforts, both from a technical perspective and a logistical one. The path forward in aeroelastic benchmarking is evolving. Future efforts will be crafted based on the findings from the workshop.

It is the shared view of the authors of the current paper that computational solution of unsteady problems are a critical area that deserves increased attention. The AePW constitutes a first step in this direction and a logical progression for those who have been involved in developing and applying methods to define the state of the art in steady aerodynamic predictions.

[§]combine or leverage, in an effort to avoid drowning

11 ACKNOWLEDGMENTS

The authors thank and acknowledge the contributions of: the computational teams who contributed to the AePW effort and continue to study these configurations; the AePW organizing committee members who have been instrumental in formulation and conduct of this workshop; Kumar Bhatia from The Boeing Company for his valuable insights into aeroelasticity, wind tunnel effects and big-picture requirements; the financial supporters (Deutsche ForschungsGemeinschaft) and colleagues at RWTH Aachen who contributed the HIRENASD experimental data set; and Dave Piatak of NASA who contributed the BSCW experimental data set. The authors also thank the NASA Fixed Wing project, the NASA Engineering and Safety Center and the NASA Aeronautical Sciences project for their financial sponsorship.

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