Aeroelasticity Benchmark Assessment
Subsonic Fixed Wing Program
Interim Report
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Introduction

The fundamental technical challenge in computational aeroelasticity is the accurate prediction of unsteady aerodynamic phenomena and the effect on the aeroelastic response of a vehicle. Currently, a benchmarking "standard" for use in validating the accuracy of computational aeroelasticity codes does not exist. Many aeroelastic data sets have been obtained in wind-tunnel and flight testing throughout the world; however, none have been globally presented or accepted as an ideal data set. There are numerous reasons for this. One reason is that often, such aeroelastic data sets focus on the aeroelastic phenomena alone (flutter, for example) and do not contain associated information such as unsteady pressures and time-correlated structural dynamic deflections. Other available data sets focus solely on the unsteady pressures and do not address the aeroelastic phenomena. Other discrepancies can include omission of relevant data, such as flutter frequency and / or the acquisition of only qualitative deflection data. In addition to these content deficiencies, all of the available data sets present both experimental and computational technical challenges. Experimental issues include facility influences, nonlinearities beyond those being modeled, and data processing. From the computational perspective, technical challenges include modeling geometric complexities, coupling between the flow and the structure, grid issues, and boundary conditions. The Aeroelasticity Benchmark Assessment task seeks to examine the existing potential experimental data sets and ultimately choose the one that is viewed as the most suitable for computational benchmarking. An initial computational evaluation of that configuration will then be performed using the Langley-developed computational fluid dynamics (CFD) software FUN3D[1] as part of its code validation process.

In addition to the benchmarking activity, this task also includes an examination of future research directions. Researchers within the Aeroelasticity Branch will examine other experimental efforts within the Subsonic Fixed Wing (SFW) program (such as testing of the NASA Common Research Model (CRM)) and other NASA programs and assess aeroelasticity issues and research topics.

Drag Prediction Workshop Review

The SFW objective addressed by the Aeroelasticity Benchmark Assessment task is the development of prediction and analysis tools for reduced uncertainty in the design process. A successful effort will result in identification of a focus problem for government, industry, and academia to all use in demonstrating and comparing codes, methodologies, and experimental information to advance the state of the art. Ideally, such a focus problem would be but the first of many put forth for this purpose, with a future goal being the design, fabrication, and testing of an aeroelastic model specifically targeting acquisition of an "ideal" data set for code validations. The desire to have such a model has already been expressed within the computational aeroelasticity community, and a committee within the NATO Research and Technology Organization (RTO) has been tasked this year (2009 – 2010) to investigate the possibility. An excellent example of this progression and escalation of code validation in the international community is the series of four AIAA CFD Drag Prediction Workshops that have been held since 2001.

As part of the Aeroelasticity Benchmark Assessment task, the history of the AIAA CFD Drag Prediction Workshop series was reviewed. The overall focus of these workshops was on increasing drag prediction accuracy. With this focus in mind, there were three objectives. The first objective was to assess the ease and practicality of using state-of-the-art computational methods for load prediction. The second objective was to evaluate the effectiveness of these Navier-Stokes-based computer codes, and the final objective was to identify areas for improvement. The first workshop occurred in June 2001 and utilized a subsonic wing/body transport configuration flying at subsonic through transonic speeds. The second workshop occurred two years later, presenting results from a more complex transport configuration incorporating nacelles. For both cases, experimental data was available for comparison with the analytical results being obtained prior to the workshop. The third workshop held in June 2006 involved "blind" drag prediction, having participants run their codes with a modified version of the configuration from the second workshop with no experimental data available before the workshop for comparison. The fourth and most recent workshop was held in June 2009. This workshop utilized a configuration designed for the sole purpose of aerodynamic CFD code prediction validation.[2] Called the NASA Common Research Model (CRM), this configuration has the following components: wing, body, nacelle, pylon, and horizontal-tail. As with the third workshop, the prediction activity was intended to be "blind", with experimental data unavailable for comparison during the analysis cycle. In this case, though, the experimental data did not yet exist as the fabrication and testing of the NASA CRM was planned as a parallel activity.[3] The first test of the CRM was recently completed in the NASA National Transonic Facility (NTF). Results of that test have not been distributed, but preliminary discussions with the test team have revealed the possibility of an aeroelastic component (a dynamic pressure effect). The Aeroelasticity Branch has begun a dialogue with the CRM test team to assess this data and provide assistance if needed. A second test of the CRM is planned in the spring of 2010 in a different facility (the Ames 11-Foot Tunnel) to help quantify experimental, facility-related uncertainty.

The structure of the Drag Prediction Workshop series provides a template for other CFD communities seeking similar improvements in accuracy within their own fields. The examination and selection of aeroelastic data sets activity within the Aeroelasticity Benchmark Assessment task is viewed as one of the first steps for initiating such a process within the computational aeroelasticity community.

Aeroelastic Experimental Data Set Assessments and Selection

As mentioned previously, many experimental aeroelastic data sets have been produced, each with its own strengths and weaknesses when viewed from the perspective of computational benchmarking. A number of these data sets have been documented in references 4 and 5. For the purposes of this task, an "excellent" aeroelastic data set has been defined as one containing (1) extensive unsteady pressure measurements, (2) quantitative displacement / deflection measurements, (3) quantitative flow visualization measurements (for example, Schlieren and off-body velocity measurements), and (4) loads measurements acquired at both subsonic and transonic conditions. The configuration tested should be simple enough that it can be modeled without adding an unnecessary level of uncertainty to the computational results. In addition, there should be a high-quality definition of the model, including (1) well-documented geometry, (2) stiffness, mass, and inertia measurements, and (3) structural dynamic properties (natural frequencies, mode shapes, and generalized mass). The type of aerodynamic and / or aeroelastic phenomena captured is also important since a validation process typically progresses from simpler to more challenging cases. The accurate prediction of unsteady aerodynamic phenomena and their effect on the aeroelastic response of a vehicle is considered the first step in the current FUN3D validation process. Subsequent steps are envisioned to include validation of static aeroelastic properties, limit-cycle oscillation (LCO), flutter, buffet, and control surface effectiveness. To be part of an "excellent" data set, these aeroelastic phenomena should have well-mapped, quantitative instability boundaries.

To begin the search for the best available data set for the FUN3D validation effort, distributable data sets from the following sources were considered: (1) those discussed in references 4 and 5, (2) those produced in wind-tunnel tests at the NASA Langley Transonic Dynamics Tunnel (TDT), and (3) those presented to the NATO Research and Technology Organization (RTO). For this interim report, only the data sets that made the "top five" will be discussed. It should be noted that the AGARD 445.6 wing data set, which has been widely used for code verification for over 20 years, was not a candidate in the current selection process. As will be discussed in a later section of this report, the AGARD 445.6 wing data set was very limited in the type of data available (primarily flutter points) and in the geometric and modal information provided, thus effectively removing it from consideration. This data set was used, however, during an initial and very limited FUN3D verification, where only one Mach number was run. This initial effort along with expanded Mach runs from the same data set generated to gain familiarity with the code will also be discussed in the later section.

NASA Langley Benchmark Models Program (BMP)

One of the data sets considered was the aeroelastic data set generated with the first three models from the NASA Langley Benchmark Models Program (BMP)[6]. The purpose of this program was to provide high-quality experimental unsteady aerodynamics data, particularly at flutter conditions, specifically to evaluate CFD codes for aeroelastic analysis. It was initiated in response to the lack of aeroelastic data sets available and suitable for validation efforts prior to 1990. This program started with of a series of three geometrically simple wing models with the same rectangular planform (32-inch span and 16-inch chord) that were tested in the TDT at transonic test conditions throughout the 1990s. The following three airfoil sections with correspondingly different transonic performance characteristics were used for models one, two, and three, respectively: the NACA 0012 airfoil, the NACA 64A010 airfoil, and the NASA SC(2)-0414 supercritical airfoil. The models were constructed from aluminum in three sections that were bolted together. For flutter testing, each model was mounted to the TDT Pitch and

Plunge Apparatus (PAPA). This mounting system consists of four flexible circular rods and permits essentially uncoupled rigid body pitch and plunge modal motions. Instrumentation consisted primarily of 80 unsteady pressure transducers, with 40 at the 60-percent span chordline and 40 at the 95-percent span chordline. Dynamic motion measurements were acquired primarily via strain gages and accelerometers attached to the PAPA mount system. Only four accelerometers were included with the wing. Each of the models was tested in both air and R-12 heavy gas, with conditions ranging from Mach 0.3 to 0.9. Angles-of-attack ranged from -3 to 5 degrees. Reynolds numbers for these tests were low, ranging between one and seven million based on the wing chord. A grit strip located at 7.5 percent chord was also tested on each wing to investigate the effect of free versus forced flow transition. There was some effort during the program to acquire flow visualization data in the form of tufts and shear-sensitive liquid crystal surface flow patterns. Overall, this is a very good aeroelastic data set and a good candidate for this task. However, it does lack two desired components: quantitative displacement measurements and loads measurements.

NASA Langley Benchmark Active Controls Technology (BACT)

Another data set considered came from the series of tests conducted in the TDT with the NASA Langley Benchmark Active Controls Technology (BACT) model[7, 8], which was also part of the Benchmark Models Program. The purpose of this testing was to acquire high-quality experimental unsteady aerodynamics data with static and dynamic control surface deflections. The model also served as a testbed for active controls research. The BACT model was based on BMP model number one, with the same dimensions, geometry, and airfoil section (NACA 0012). The BACT model, however, incorporated three hydraulically-actuated active control surfaces: a 25-percent chord trailing-edge control surface, a 15-percent chord upper surface spoiler, and a matching 15-percent chord lower surface spoiler. The spoilers were hinged at 60-percent chord, and all three surfaces extended between the 45- and 75-percent span stations. The wing portion of this model was machined from aluminum, while the control surfaces were of composite construction. As with the previous BMP models, the BACT model was instrumented with unsteady pressures at two chordlines. In this case, however, the majority of the transducers (58 of them) were located at the 60-percent span station, which was the midspan of the control surfaces. Seventeen additional unsteady pressures were located at the 40-percent span station over the aft portion of the chord (60- to 95-percent chord stations) to measure loading near the control surface edges. The BACT model was tested on both a rigid strut for force balance measurements and on the TDT PAPA mount system for flutter and forced response data. The model was tested primarily in R-12 heavy gas, with only a limited amount of data in air. Conditions ranged from Mach 0.63 to 0.94. Angles-of-attack ranged from -4 to 10 degrees. Static trailing-edge control surface and spoiler deflections ranged from -10 to 12 degrees and 0 to 40 degrees, respectively. Dynamic oscillations at frequencies up to 10Hz were achieved with all three control surfaces, with amplitudes of 1 to 4 degrees for the trailing-edge control surface and up to 10 degrees for the two spoilers. A grit strip located at 5 percent chord was present throughout testing. Overall, this is another very good aeroelastic data set from the BMP, particularly for computational studies involving fixed-deflection and oscillating control surfaces. However, it lacks two desired components for the Aeroelasticity Benchmark Assessment task: quantitative displacement measurements and flow visualization measurements.

NASA High-Speed Research (HSR) Program

The extensive aeroelastic data set generated by the NASA High-Speed Research (HSR) program was also considered. Under this program, two models, the Rigid Semispan Model (RSM) and the Flexible Semispan Model (FSM), were tested to acquire unsteady pressure data for both computational code evaluations and design method correlations.[9] These two models had virtually the same geometry and instrumentation. The designed difference was the model stiffness. The HSR-RSM was very stiff to intentionally minimize aeroelastic deflections. The HSR-FSM, on the other hand, had a flexible structure that was aeroelastically-scaled to anticipated flight conditions. The wings for both models were based on a high-speed civil transport planform and were constructed of composite materials. A rigid fuselage fairing was also used with each wing during the tests to ensure that the wing root was outside the tunnel wall boundary layer and to provide a realistic aerodynamic boundary condition. In addition to a clean-wing configuration, each model could be fitted with a pair of flow-through nacelles, and both wings incorporated a hydraulically-actuated inboard trailing-edge control surface that could be oscillated to generate unsteady aerodynamics data. The HSR-RSM was wall-mounted in the TDT using either a turntable / balance attachment, the TDT PAPA mount system, or the TDT Oscillating Turntable (OTT). The HSR-FSM was primarily tested for flutter on a rigid strut attached to the turntable, with some limited subcritical response testing performed on the balance. Both models were instrumented with 131 unsteady pressure transducers that were distributed chordwise at four span stations (10-, 30-, 60-, and 95-percent span). Both the RSM and FSM wings also contained 14 accelerometers distributed throughout the planform. To capture steady pressures on the rigid fuselage fairing, 120 steady pressure orifices were included at seven fuselage stations. Due to the flexible structure of the FSM wing, it was additionally instrumented with four strain gages (one torsion and three bending). Several optical targets were also attached near the wing tip for deflection measurements.

Testing of the HSR-RSM and HSR-FSM models in both air and heavy gas (R-12 in 1996 and R-134a after 1997) in the TDT began in 1996 and continued through 2000. Data was acquired for the HSR-RSM from M = 0.6 – 1.15 at dynamic pressures of 100, 150, and 200 psf. Steady data was acquired at angles of attack from -5 to 8 degrees and control surface deflections from -5 to 5 degrees. Unsteady aerodynamics data was acquired from forced oscillation of the control surface at 0.25, 1, 2, and 5 degrees with frequencies of 1, 2, 5, or 10 Hz. Data was acquired for the HSR-FSM from M = 0.8 – 1.15 at dynamic pressures of 100, 125, and 150 psf. Steady data was acquired at angles of attack from -1 to 2.5 degrees and control surface deflections of -4 to 4 degrees. Forced oscillations for this configuration were conducted at various combinations of control surface angle and frequency.[10, 11]

The aeroelastic data set generated from the HSR program is very good, providing both static and dynamic aeroelastic information for a computationally interesting planform. It includes extensive unsteady pressure data, displacement measurements at the wingtip, and loads measurements from both a balance and wing strain gages, but it lacks flow visualization. In addition, the construction of these wind-tunnel models, particularly the FSM, is geometrically complex with lockouts and flexible couplings that are difficult to model analytically. For a code validation effort, it was decided that this would add an unnecessary level of uncertainty.

Consequently, it was removed from consideration as the initial data set. It would be a good candidate for more intensive validation efforts in the future, though.

High Reynolds Number Aero-Structural Dynamics (HIRENASD) Project

The data set generated in the European Transonic Windtunnel (ETW) through the High Reynolds Number Aero-Structural Dynamics (HIRENASD) Project[12, 13, 14] was also considered. This project, led by the Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University's Department of Mechanics (LFM) with funding from the German Research Foundation (DFG), was initiated in 2004 to produce a high-quality transonic aeroelastic data set at realistic flight Reynolds numbers for a large transport-type wing/body configuration. Ultimate free and open distribution of the published data from this effort was also a top priority of the researchers involved. The HIRENASD wing planform, shown in Figure 1, is a ceiling-mounted, semi-span clean-wing configuration with a leading-edge sweep of 34 degrees, a span of 4.22 feet, and a mean aerodynamic chord of 1.13 feet. It consists of three sections. The two outboard sections utilize an 11-percent thick BAC 3-11/RES/30/21 supercritical airfoil. The inboard section uses the same airfoil thickened linearly from 11-percent at its outer edge (11.25-inch span station) to 15-percent at the root. To minimize boundary layer interference, a generic fuselage was included. It extended 3.54 inches from the tunnel ceiling and was mechanically isolated from the wing by a labyrinth seal. The span of the entire assembly from the tunnel ceiling was 4.51 feet. Extensive measurements were acquired during testing of the HIRENASD model. Instrumentation included a six-component balance, Surface Pattern Tracking (SPT) optical markers for surface deformation measurements on the pressure side of the wing, 11 accelerometers, 28 strain gages, and 259 unsteady pressure transducers. The pressure transducers were distributed along the upper and lower surfaces at seven span stations (7.34, 16.34, 23.08, 29.82, 33.17, 40.71, and 48.26 inches).

Testing of the HIRENASD wind-tunnel model occurred in the ETW in 2006. The test matrix consisted of both static and dynamic measurements at different flow conditions, with variations of Reynolds number (up to 73 million based on the mean aerodynamic chord) and dynamic pressure (up to 2715 psf) at six transonic Mach numbers: 0.70, 0.75, 0.80, 0.83, 0.85, and 0.88. The test medium was nitrogen. For static testing, pressure distribution and lift and drag polars were acquired at angles of attack from -2 to 5 degrees. Dynamic testing involved forced vibrations of the wing at the first bending, second bending, and first torsion modes and was performed at the zero lift angle of attack of -1.34 degrees.

Ultimately, the data set generated via the HIRENASD Project is very attractive for the SFW Aeroelasticity Benchmark Assessment task, with a good distribution of unsteady pressure measurements, deflection measurements, and balance loads measurements at transonic conditions with realistic flight Reynolds numbers. The only item lacking from the "wish list" is flow visualization. Another benefit of this data set is the existence and availability of both a CFD grid and finite element model (FEM), reducing the preparation time needed before CFD runs could commence.

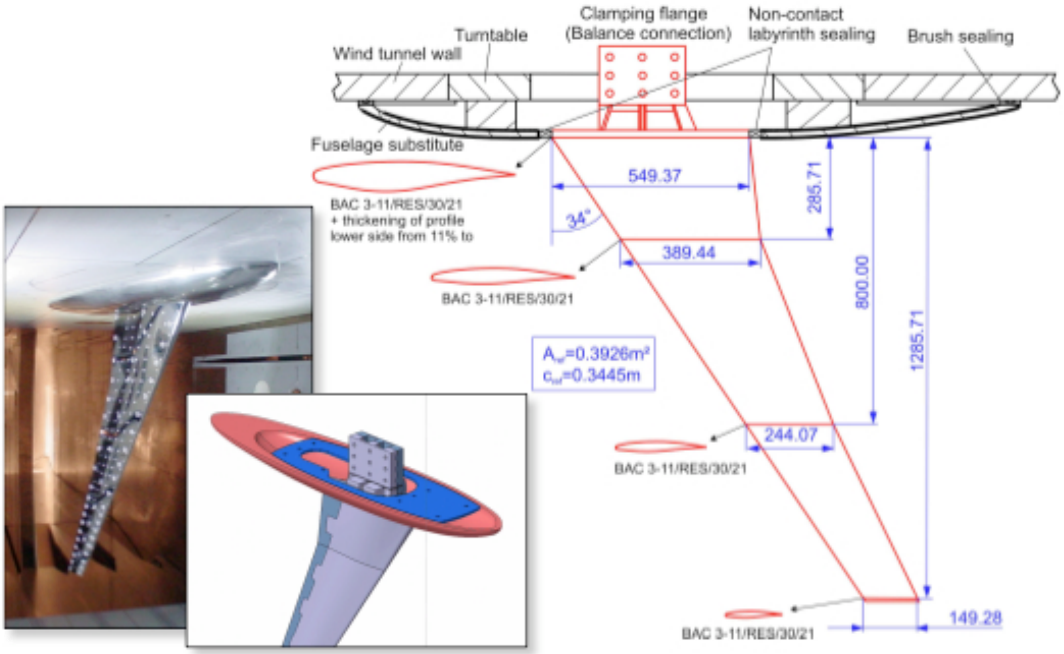


Figure 1. HIRENASD wing model planform, assembly, and ETW installation photo.
NOTE: Dimensions shown are in millimeters.

NASA Langley Models for Aeroelastic Validation Research Involving Computations (MAVRIC) Program

A fifth candidate data set considered in the assessment and selection process was the one generated by NASA Langley's Models for Aeroelastic Validation Research Involving Computations (MAVRIC) program.[15, 16, 17] This program was specifically devised and implemented in the late 1990s through 2000 to produce high-quality experimental data for higher-level computational aeroelastic code validations at transonic flow separation onset conditions. For this program, researchers started with an existing aeroelastically-scaled model of a business jet wing that had previously been tested in the TDT in 1993 and 1994, modifying it to include unsteady pressures and a more aerodynamically streamlined lower fuselage. This model was chosen for its simple plate model construction and its demonstrated flutter and limit-cycle oscillation (LCO) behavior in the 0.80 to 0.90 transonic Mach number range. The MAVRIC model, shown in Figure 2, is a semi-span, sidewall-mounted model with a span of 53.17 inches, a taper ratio of 0.29, a midchord sweep angle of 23 degrees, and no twist or dihedral. The wing is constructed of an aluminum plate, stepping in thickness from 0.276 inches at the root to 0.106 inches at the tip in four increments across the span. Shaped endgrain balsa wood was glued to the plate to provide the wing contour. The wing was mounted low on a fuselage body of revolution that included a four-inch standoff section to account for the tunnel wall boundary layer. Three wingtip configurations were used during testing: (1) a "clean" tip of revolution cap, (2) a 75-degree canted, swept winglet, and (3) a 0.5-inch cylindrical tip "pencil" store. Eightyfour two-psi unsteady pressure transducers were incorporated into the wing during the model refurbishment. These were distributed along three chords at 22-, 63-, and 88-percent span, with 17 transducers on the upper surface, 10 on the lower surface, and 1 at the trailing edge at each chord. Additional model instrumentation included 8 miniature accelerometers mounted near the leading and trailing edges at 26-, 45-, 68-, and 90-percent span, bending and torsion strain gages at the wing root, and two angle-of-attack sensors. Fifteen optical targets were placed on the model's lower surface along 5 rows (3 targets per row) to acquire dynamic deformation measurements using the NASA Langley-developed Videogrammetric Model Deformation (VMD) system.[18] This system captured these deformations at a rate of 60 frames per second. Tufts were added to the wing and fuselage during the latter portion of the test to visualize flow separation. Instrumentation was also utilized to help assess tunnel wall and plenum influences on the model data. For this purpose, seven pressure transducers were mounted along the sidewalls (4 in the east wall, 1 in the west wall, and 1 each in the floor and ceiling), and four B&K microphones were installed in the plenum.

MAVRIC model testing was conducted in both air and R-134a heavy gas in the TDT in June 2000. Comparison of results in the two mediums provided data on Reynolds number effects, flow transition effects, and the effect of speed of sound on LCO behavior. Traditional flutter boundaries were measured at Mach numbers from 0.6 to 0.9, and maps of LCO behavior were made at Mach numbers from 0.85 to 0.95. Testing was performed primarily at three angles of attack: 0.6 degrees (zero wing loading), 1.6 degrees, and 2.1 degrees. VMD data was not acquired for all conditions due to initial difficulties in setting up the system. This data only exists for the latter half of the testing in R-134a.

Like the HIRENASD data set, the MAVRIC data set is very attractive for the SFW Aeroelasticity Benchmark Assessment task. It includes a good distribution of unsteady pressure transducers (located both on the model and in the tunnel walls), dynamic deflection measurements, loads measurements via root strain gages, and some qualitative flow visualization from tufts. There are restrictions on the distribution of data involving the winglet configuration since it is proprietary with the original manufacturer, but the other two configurations are available. For the current benchmarking task, however, the LCO and flutter model behavior offered with this data set represents a more challenging class of phenomena to predict computationally. The MAVRIC data set is therefore not the ideal set required for the unsteady aerodynamic phenomena prediction considered to be the first step in the current FUN3D verification process. It would be a top candidate, though, for further steps along the validation path.

Figure 2. Photos of the MAVRIC model installed in the TDT.

Data Set Selection

The first data set selected to follow the AGARD 445.6 wing work for FUN3D code validation is HIRENASD. After reviewing the planning, development, testing, and published results of this project, it was determined that this data set was the best candidate for the first step in the current validation process: accurate prediction of unsteady aerodynamic phenomena and their effect on the aeroelastic response of a vehicle. Obvious benefits from this data set include the extensive, high-quality measurements and available CFD grid and FEM. Another benefit is that this data was generated via a large cooperative effort in the ETW and has been available to the international CFD community for several years. There is therefore an opportunity here to have aeroelastic CFD code assessments using HIRENASD data serve as the foundation for a workshop series similar to those of the Drag Prediction Workshop series. In addition, the HIRENASD testing in the ETW is planned to continue, with the original configuration modified to include a winglet equipped with a control surface, as shown in Figure 3.[19] The MAVRIC data set has been selected as the best candidate for follow-on validation work, specifically the accurate prediction of LCO and flutter. Preparation of this data set, FEM, and CFD grid are being worked concurrently with the HIRENASD computational benchmarking.

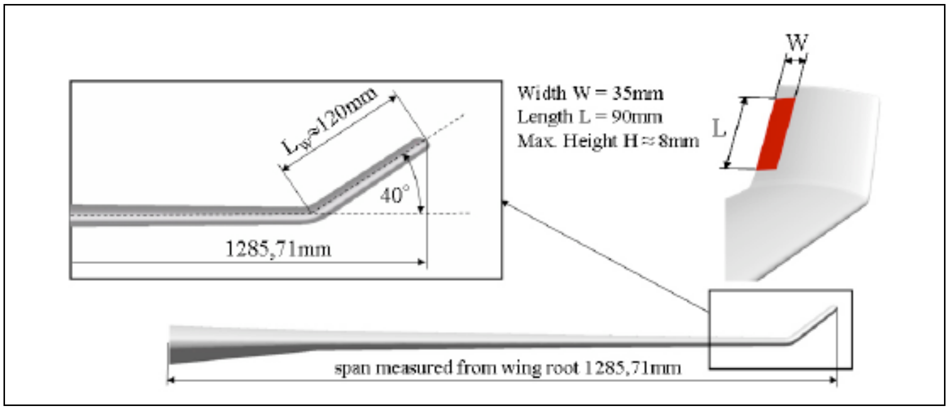


Figure 3. Planned configuration-2 HIRENASD model modifications.

Finite Element Model (FEM) Analysis and FUN3D Validation Efforts

AGARD 445.6 Wing Data Set

As previously discussed, for verification of any aeroelastic CFD code, it is essential to have good experimental data cases available. One flutter test case that has been publicly available for over 20 years is the AGARD 445.6 wing.[20, 21] This wing planform was sidewall-mounted, had a quarter-chord sweep angle of 45 degrees, a panel aspect ratio of 1.65, and a taper ratio of 0.66. It was flutter tested in the TDT in both air and R-12 heavy gas at Mach numbers from 0.34 to 1.14. Since it became available, this configuration has been widely used for preliminary computational benchmarking. Unfortunately, many of its flutter data sets lack sufficient geometric or modal information for more extensive code validations.[22]

When the FUN3D code was initially exercised for validation in the year 2006, the AGARD 445.6 wing test case was utilized. This validation was extremely limited, however, using only one Mach number condition. In preparation for FUN3D validation using the HIRENASD and MAVRIC data sets, validation runs using the AGARD 445.6 wing were performed across the entire range of the experimental data. Figures 4 and 5 show comparisons of the flutter speed index and frequency ratio values, respectively, obtained from previous CFD work, the current FUN3D predictions, and the experimental data. The flutter speed index scales the flutter dynamic pressure, and the frequency ratio scales the flutter frequency. In general, in the subsonic flow regime, the computational data matches the experimental data well. A broad range in the computational data is observed in the transonic and supersonic flow regimes.

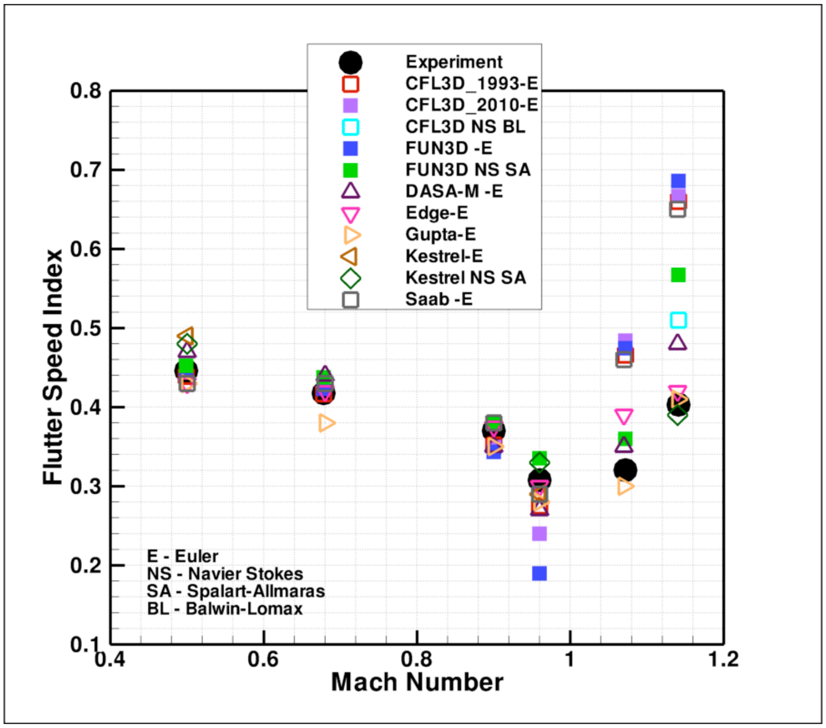


Figure 4. Flutter speed index (flutter dynamic pressure scaling) versus Mach number as computed by others and compared with FUN3D and experimental data.

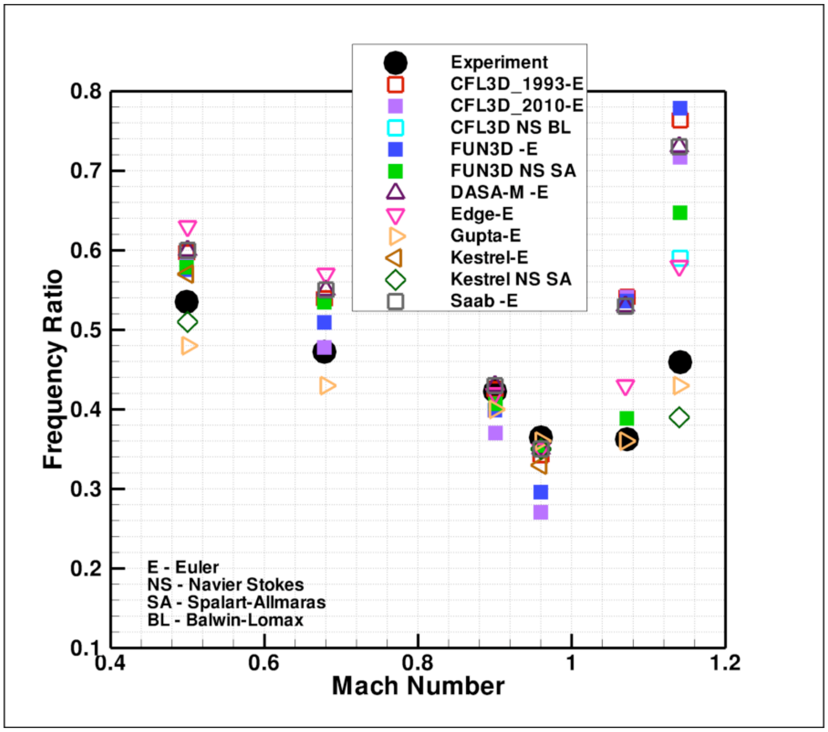


Figure 5. Frequency ratio (flutter frequency scaling) versus Mach number as computed by others and compared with FUN3D and experimental data.

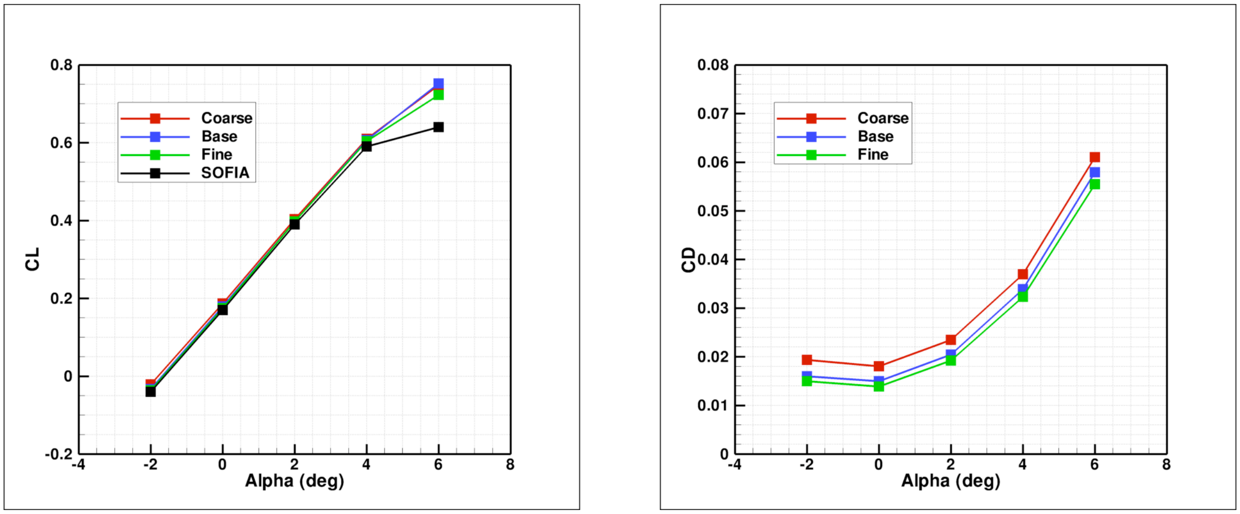
HIRENASD Data Set

Testing of the HIRENASD wind-tunnel model occurred in the ETW in 2006. Numerous papers have been published since then documenting a scattering of the results at a few of the test conditions. (See references 12-14, 19, and 23.) A complete data set for the published test conditions has been requested but not yet received from the HIRENASD Project lead researcher, Dr. Josef Ballmann. Unpublished test conditions have not been released. The finite element models (FEMs), grid used with the CFD software SOFIA, sensor locations, pressure port locations, and test matrix were obtained from the publicly available HIRENASD Project website, shown as reference 24.

Two different FEMs are available from the HIRENASD website. Both are modeled with uniform solid elements. One FEM uses NASTRAN hexagonal elements, has over 200k grid points, and uses a coordinate system in millimeters. The other FEM uses NASTRAN tetrahedral elements, has approximately 170k grid points, and uses a coordinate system in meters. The two FEMs yield slightly different modal frequencies. However, these differences are small (less than 1.3 percent), and the first ten mode shapes are virtually identical. Interestingly, these modes don't exactly match those shown in the published reports because the boundary condition in both available FEMs is different from the one used to generate that data. A current "best FEM" has been requested.

To facilitate future linear aeroelastic calculations and interpolation of the mode shapes from the FEMs to the CFD locations, all of the grid locations were converted to a consistent aerodynamic coordinate system in meters, where x is in the flow direction, y is out the span, and z is up. The required material card was also changed for the model that was converted from millimeters to meters. Future planned FEM investigations include further modal analysis, static aeroelastic analyses, and forced oscillations of the entire wing.

The initial, rigid body computations on the HIRENASD geometry using FUN3D are completed. The lift and drag computations obtained across the angle of attack range at M = 0.8 and Reynolds number = 23.5 x 10^6 (based on the mean aerodynamic chord) for three grid resolutions of 5 (coarse grid), 10 (base grid), and 20 (fine grid) million nodes are shown in Figures 6a and 6b, respectively. In Figure 6a, the lift coefficient calculations are compared to the published rigid body computational data generated by the CFD software SOFIA, which is provided in reference 23. Unfortunately, similar drag coefficient data is not shown in Figure 6b since it has not been published and has yet to be provided as part of the releasable data set by the HIRENASD team. The grid resolution study indicates that the FUN3D solutions are not grid converged in drag coefficient, and perhaps one more grid resolution is needed. However, in this study, the fine grid will be used as the baseline grid for aeroelastic computations. The discrepancy in lift coefficient between FUN3D and SOFIA results shown in Figure 6a is due to the turbulence model used in the analysis. The effects of different turbulence models will be investigated. Figure 7 shows a computed coefficient of pressure at one condition of interest: Mach = 0.8, alpha = 4 degrees, and Reynolds number = 23.5 x 10^6 (based on the mean aerodynamic chord).



(a) Lift coefficients versus alpha.

(b) Drag coefficients versus alpha.

Figure 6. FUN3D-computed lift and drag coefficients for the HIRENASD configuration. Tunnel condition: M = 0.8, Reynolds number = 23.5 x 10^6 (based on the mean aerodynamic chord).

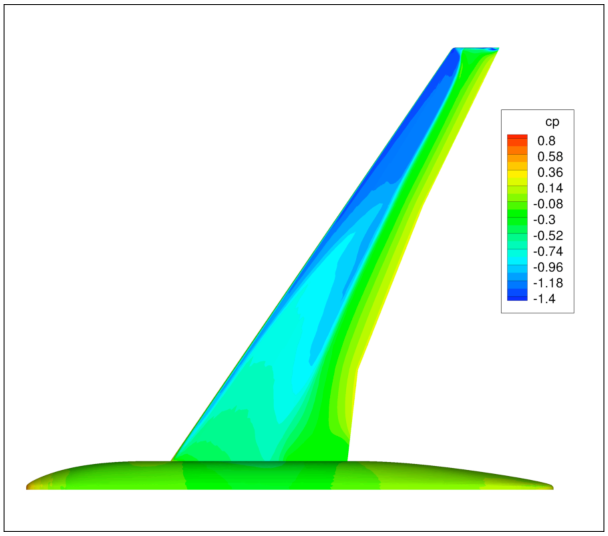


Figure 7. Sample FUN3D calculation of coefficient of pressure at M = 0.8, alpha = 4 degrees, and Reynolds number = 23.5 x 10^6 (based on the mean aerodynamic chord).

Work being performed at the present time is concentrated on mode shape mapping from the FEM to the CFD grid and the subsequent static aeroelastic computations. Figure 8 shows an example of the first-bending mode mapped from the NASTRAN FEM into the CFD grid.

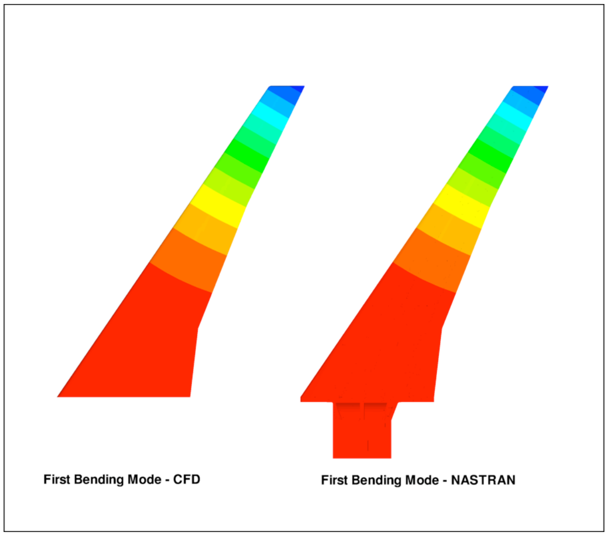


Figure 8. HIRENASD model first-bending mode mapped from the NASTRAN FEM into the CFD grid.

MAVRIC Data Set

Testing of the MAVRIC wind-tunnel model occurred in the TDT in June 2000. The data was subsequently analyzed, and several papers were published. (See references 15-18.) However, a comprehensive, releasable data set was never prepared, and the lead researchers on this program have since retired or moved to different organizations within NASA Langley. Consequently, challenges have been encountered in resurrecting and understanding the data and existing documentation that is available.

Three original FEMs have been located and verified for the three MAVRIC configurations that correspond to the three different wingtips (clean-wing tip of revolution, winglet, and pencil store). The clean-wing FEM is shown in Figure 9. In addition, there is an independent clean-wing FEM being developed by the University of Illinois, Champaign, which now has possession of the model and is performing work with it under an STTR. This FEM will be available for use as well. Considering the data restrictions discussed previously and the desire to keep things as simple as possible, only the clean-wing configuration will be used for the current Aeroelasticity Benchmark Assessment task. To date, information from the flutter and modal analyses performed in the past has been collected. Several of these cases have been re-run for verification, and additional analyses with the FEM will be done as needed to support the FUN3D validation effort.

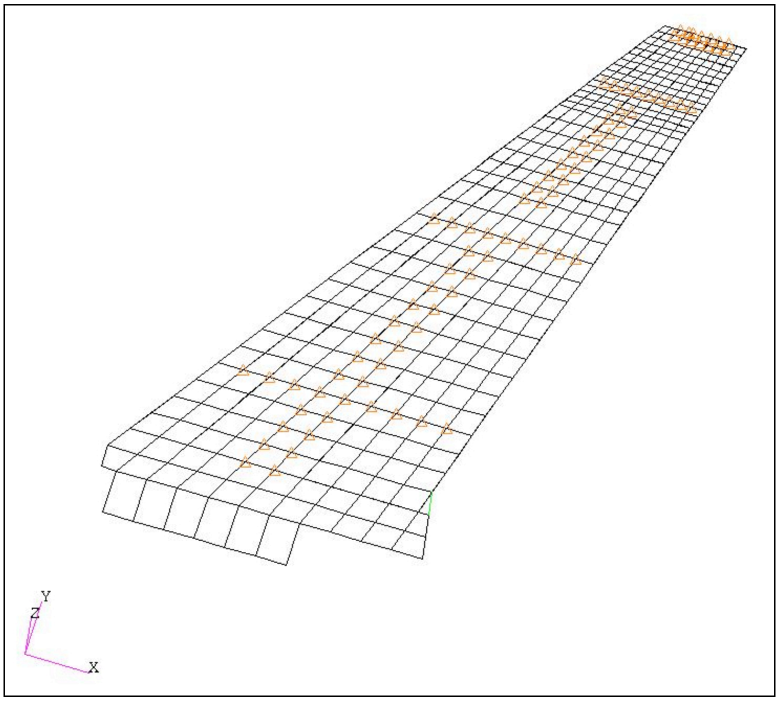


Figure 9. The MAVRIC clean-wing FEM.

A review, evaluation, and cataloging of the experimental data is also ongoing. The wind-tunnel data was acquired using three data acquisition systems. The first system (DAS-1), which sampled at 1000 Hz, captured all data channels except those associated with VMD. The second system (DAS-2) sampled only a limited number of channels at 5000 Hz in order to ascertain differences due to the sampling rate. The VMD system represents the third data acquisition system. To date, tools have been resurrected to visualize the data from all three systems, and a data mining code is being implemented to assess data availability from each system and to help identify points of interest and data trends. The major task with the experimental data is to identify nominal conditions and conditions of interest that will make up the core of a releasable data set. To assist in this effort, the MAVRIC program lead engineer, Dr. John Edwards, who is currently a NASA Distinguished Research Associate (DRA), has provided guidance is navigating through the forest of information collected in binders from ten years ago. He is also assisting in the identification of the “interesting” tunnel conditions / data points.

Published data for the MAVRIC program shows analytical results generated primarily using the FEM and linear doublet lattice aerodynamics. Computations were also performed with the Computational Aeroelasticity Program – Transonic Small Disturbance (CAP-TSD) code, which uses an interactive quasi-steady boundary-layer method coupled with a transonic small disturbance code. No other CFD efforts were initiated. Unfortunately, the grid generated from the CAP-TSD runs is not sufficient for or even compatible with other CFD codes, so grid development for the Aeroelasticity Benchmark Assessment task will be from scratch. The first step in this process was to create a computer-aided design (CAD) model of the clean-wing configuration. Unfortunately, this was not a straightforward task since a complete outer-mold-line definition was unavailable. Using drawings from the model refurbishment, an incomplete set of measured ordinates, information from tunnel installation photographs, and measurements provided by the University of Illinois, Champaign (where the model temporarily resides), the GEOLAB at NASA Langley was able to build the desired CAD model, shown in Figure 10. This was completed the week of March 15, 2010. The next step, also to be performed by the GEOLAB, is the generation of an unstructured grid.

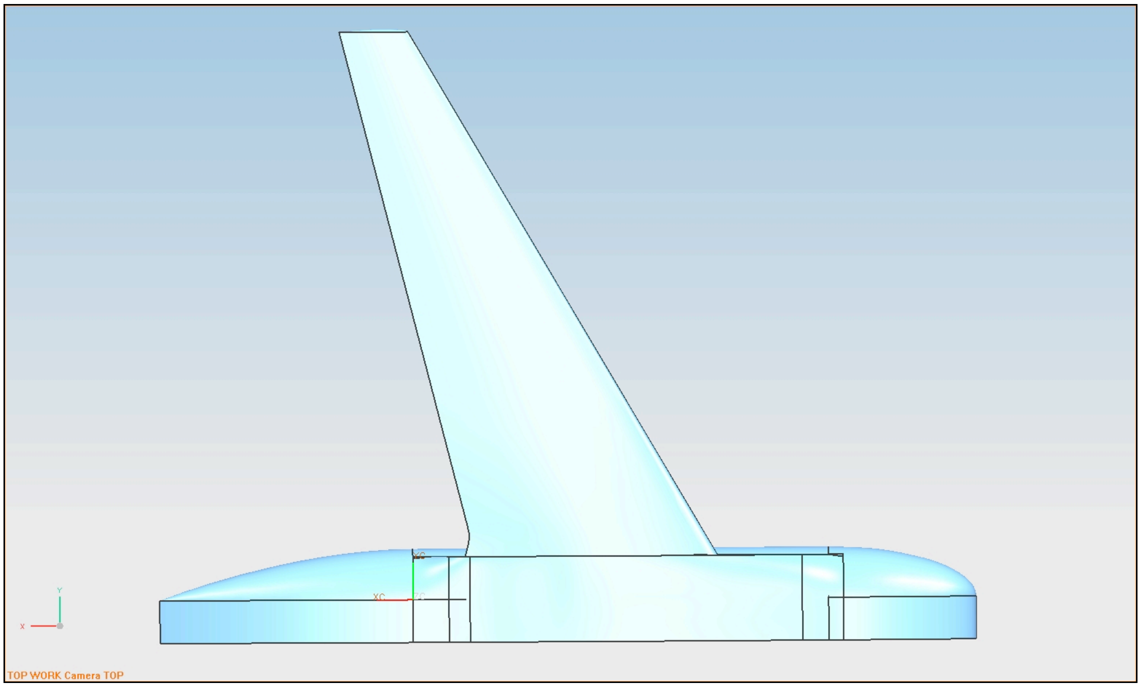


Figure 10. CAD model of the MAVRIC clean-wing configuration.

Future Work

In the remaining six months of the current fiscal year, both FEM and FUN3D work will continue for both the HIRENASD and MAVRIC test cases. The review, evaluation, and cataloging of the

MAVRIC experimental data will also continue, beginning the process of producing a MAVRIC comprehensive data set package suitable for eventual distribution. In addition, the design, fabrication, and testing (in TDT and possibly ETW) of an aeroelastic model based on the NASA CRM planform will be advocated to the SFW program. Such a data set offering a wide distribution of unsteady pressures, deflection measurements, flow visualization, and loads data would be incredibly valuable to the computational aeroelasticity community. It would also be a natural extension to the wind-tunnel testing and CFD work already performed on this planform as part of the AIAA Drag Prediction Workshop series.

Over the next five years, it is envisioned that the Aeroelasticity Benchmark Assessment task will mature and expand into an international activity, similar to the AIAA CFD Drag Prediction Workshop series. A rough timeline for this five-year plan is shown in Figure 11. Details for each fiscal year are listed below.

FY11

- Continue validation work with HIRENASD and MAVRIC, studying the effects of tunnel condition variations, grid variations, number of subiterations, etc.
- Complete the MAVRIC comprehensive data set package.
- Through STTR work by the University of Illinois, Champaign, there is interest in testing the MAVRIC model again in the TDT. If funding is secured for such a test, then participate in the wind-tunnel test planning and entry.
- If funding is secured, initiate the design and fabrication of the aeroelastic CRM (AeCRM).
- Advocate for a Computational Aeroelasticity Workshop series.
- Monitor the progress of the NATO RTO in its pursuit of the design, fabrication, and testing of an aeroelastic model specifically for computational aeroelasticity validations. Is the interest still there? Has a funding mechanism been identified? Has a design been initiated? Participate if appropriate.

FY12

- Prepare for the first Computational Aeroelasticity Workshop. An excellent configuration would be the HIRENASD model.
- Complete fabrication of the aeroelastic CRM (AeCRM), conduct ground testing, and begin wind-tunnel testing in the TDT.
- Incorporate the new MAVRIC data from the University of Illinois, Champaign test into the comprehensive data set.
- Produce a report on the MAVRIC data set.
- Continue monitoring progress of the NATO RTO computational aeroelasticity wind-tunnel model effort, participating when possible. It is envisioned that if funding was secured in FY11, then model design would be accomplished this year.

FY13

- Participate in the first Computational Aeroelasticity Workshop.
- Update / improve the computational aeroelasticity codes based on results from the first workshop.
- Produce a report on the CFD results presented at the workshop.

- Conduct test number 2 of the aeroelastic CRM (AeCRM) in the TDT.
- Analyze, compile, and begin documenting results from the AeCRM tests.
- Continue monitoring progress of the NATO RTO computational aeroelasticity wind-tunnel model effort, participating when possible. It is envisioned that if the model design was completed in FY12, then fabrication of the model would be accomplished this year. The Aeroelasticity Branch through the SFW program would potentially have a leading role in this effort, similar to NASA Langley's role in the fabrication and testing of the NASA Common Research Model.

FY14

- Prepare for the second Computational Aeroelasticity Workshop. An excellent configuration would be the MAVRIC clean wing. If sufficient experimental data exists, the aeroelastic CRM could also be a candidate, but it would probably be more appropriate for the third Computational Aeroelasticity Workshop, envisioned to be held in FY17.
- Continue testing of the aeroelastic CRM (AeCRM) in the ETW (or other applicable facility).
- Continue analyzing, compiling, and documenting results from the AeCRM tests.
- Continue monitoring progress of the NATO RTO computational aeroelasticity wind-tunnel model effort, participating when possible. It is envisioned that if the model fabrication was completed in FY13, then testing of the model could begin this year in the TDT or the ETW. The Aeroelasticity Branch (AB) through the SFW program would lead this test. AB would also participate in analyzing and compiling the test results and assist in both the FEM and CFD grid development.

FY15

- Participate in the second Computational Aeroelasticity Workshop.
- Update / improve the computational aeroelasticity codes based on results from the second workshop.
- Produce a report on the CFD results presented at the workshop.
- Continue testing of the aeroelastic CRM (AeCRM) at AEDC (or other applicable facility).
- Continue analyzing, compiling, and documenting results from the AeCRM tests.
- Continue monitoring progress of the NATO RTO computational aeroelasticity wind-tunnel model effort, participating when possible. It is envisioned that testing would continue this fiscal year in the TDT and / or the ETW. Analysis of test results would also continue, and documentation would begin.

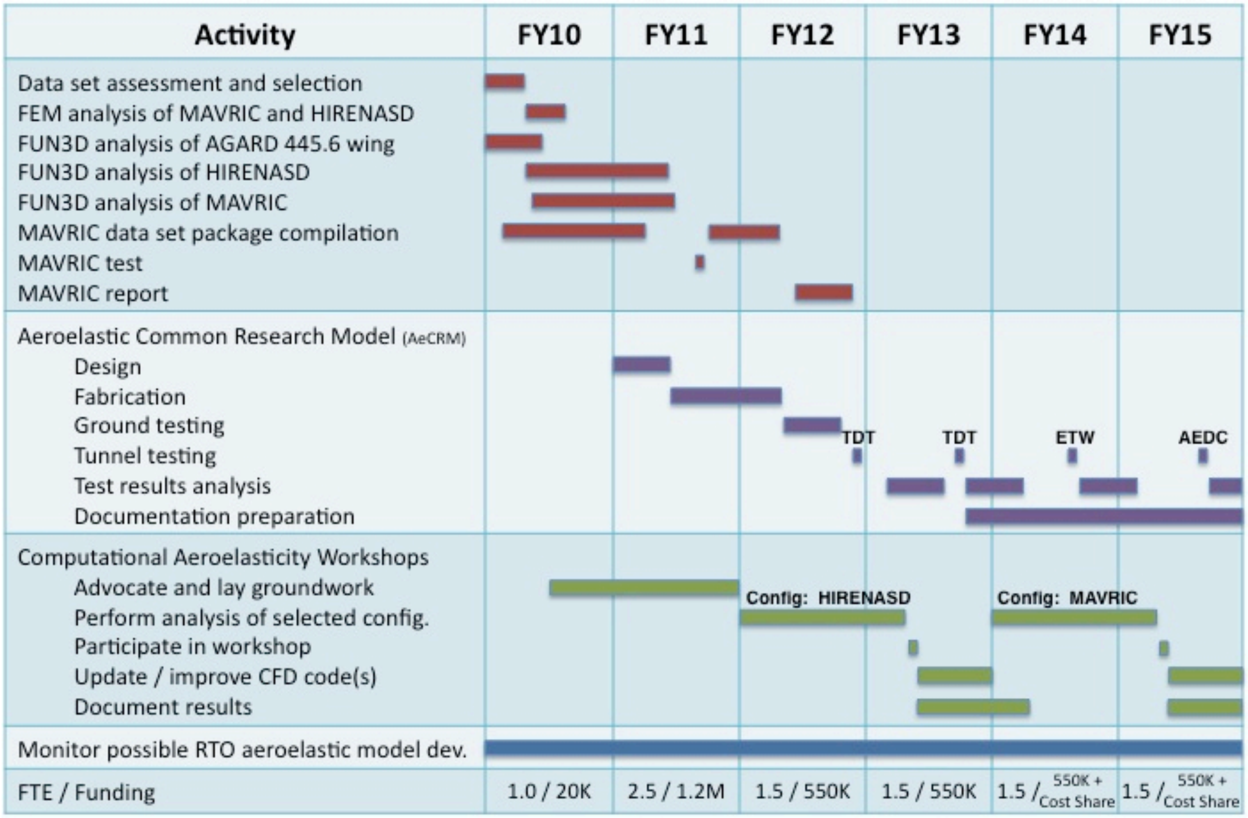


Figure 11. Aeroelasticity Benchmark Assessment Task: Future work with 5-year plan.

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