DOI: 10.13009/EUCASS2023-055
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

A Brief Summary Data from the Seventh AIAA CFD Drag Prediction Workshop

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Abstract

Results from the Seventh AIAA CFD Drag Prediction Workshop – Expanding the Envelope – are presented. These cases focused on force/moment and pressure predictions for the NASA Common Research Model wing-body configuration. The Common Research Model geometry was deformed to the appropriate static aeroelastic twist and deflection at each specified angle-of-attack. The grid refinement study (Case 1) used a common set of overset, multiblock structured, and unstructured grids, as well as user created unstructured and structured based grids. Solutions were requested for the wing-body at a fixed Mach number and lift coefficient near buffet onset. The wing-body static aeroelastic/buffet study (Case 2) specified an angle-of-attack sweep at finely spaced intervals through the zone where wing shock-induced separation was expected to begin. Case 3 requested a Reynolds number/dynamic pressure sweep at a constant lift coefficient. The optional Case 4 requested grid adaption solutions of the wing-body at a specified flight condition. Optional Case 5

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requested solutions beyond steady RANS. Optional Case 6 requested coupled aerostructural wing-body solutions. Results from this workshop highlight the progress made since the last workshop in 2016, and the continuing need for CFD improvement, particularly for conditions with significant flow separation, and close to buffet onset. These comparisons also suggest the need for improved experimental diagnostics to guide future CFD development.

1. Introduction

The AIAA CFD Drag Prediction Workshop (DPW) Series was initiated by a working group of members from the Applied Aerodynamics Technical Committee of the American Institute of Aeronautics and Astronautics. The primary goal of the workshop series is to assess the state-of-the-art of modern computational fluid dynamics methods using geometries and conditions relevant to commercial aircraft. From the onset, the DPW organizing committee has adhered to a primary set of guidelines and objectives for the DPW series:

- Assess state-of-the-art Computational Fluid Dynamics (CFD) methods as practical aerodynamic tools for the prediction of forces and moments on industry-relevant geometries, with a focus on absolute drag.
- Provide an impartial international forum for evaluating the effectiveness of CFD Reynolds Averaged Navier-Stokes solvers, as well as more advanced methods.
- Promote balanced participation across academia, government labs, and industry.
- Use common public-domain subject geometries, simple enough to permit high-fidelity computations but relevant for industry.
- Provide baseline grids to encourage participation and help reduce variability of CFD results.
- Openly discuss and identify areas needing additional research and development.
- Conduct rigorous statistical analyses of CFD results to establish confidence levels in predictions.
- Schedule open-forum sessions to further engage interaction among all interested parties.
- Maintain a public-domain accessible database of geometries, grids, and results.
- Document workshop findings; disseminate this information through publications and presentations.

Six previous workshops have been held prior to the present study, all held in conjunction with the AIAA Applied Aerodynamics Conference for that year.

Year	Location	Configuration	Case Descriptions
2001	Anaheim, CA	DLR-F4 Wing-Body	Single Point Drag Prediction Drag Polar Drag Rise Curves at Constant C_L*
2003	Orlando, FL	DLR-F6 Wing-Body Wing-Body-Nacelle	Single Point Grid Convergence Study Drag Polar Boundary Layer Trip Study* Drag Rise Curves at Constant C_L*
2006	San Francisco, CA	DLR-F6 Wing-Body with and without FX2B fairing; W1/W2 Wing Alone	Single Point Grid Convergence Study Drag Polar Grid Convergence Study Drag Polar
2009	San Antonio, TX	NASA Common Research Model Wing-Body and Wing-Body-Tail	Grid Convergence Study Downwash Study Mach Sweep Study* Reynolds Number Study*
2012	New Orleans, LA	NASA Common Research Model Wing-Body 2-D Flat Plate*,2-D Bump-in-channel*,2-D NACA 0012 Airfoil*	Grid Convergence Study Alpha Sweep Buffet Study Turbulence Model Verification*
2016	Washington DC	NASA Common Research Model Wing-Body and Wing-Body-Nacelle-Pylon 2-D NACA 0012 Airfoil	Grid Convergence Study Nacelle-Pylon Drag Increment Study Alpha Sweep Buffet Study Solution Adaption Grid Study* Coupled Aero-Structural Analysis Study* Turbulence Model Verification

*Optional Cases

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While there have been some variations, the workshops have typically used subjects based on commercial transport wing-body configurations - a consensus of the organizing committee based on a reasonable compromise between simplicity and industry relevance. With very few exceptions the participants submit results generated with Reynolds Averaged Navier-Stokes (RANS) codes, although the organizing committee does not restrict the methodology.

The first Drag Prediction Workshop [1] used the DLR-F4 geometry for the above reasons and due to the availability of publicly released geometry and wind tunnel results [2]. The focus of the workshop was to compare absolute drag predictions, including the variation due to grid type and turbulence model type. The results were also compared directly to the available wind tunnel data. A summary of these results was documented by the DPW-I organizing committee [3]. Because of strong participation, DPW-I successfully amassed a CFD data set suitable for statistical analysis [4]. However, the results of that analysis were rather disappointing, showing a 270-drag-count (a drag count = 0.0001 C_D) spread in the fixed-C_L data, with a 100:1 confidence interval of more than ±50 drag counts.

The interest generated from the workshop was continued and resulted in several individual efforts documenting results more formally [5-8], presented at a special session of the 2002 AIAA Aerospace Sciences Meeting and Exhibit in Reno, NV.

The second workshop [9] used the DLR-F6 as the subject geometry in both wing-body (WB, like DLR-F4) and wing-body-nacelle-pylon (WBNP) form. The results from the workshop were documented with a summary paper [10], a statistical analysis [11], an invited reflections paper [12] on the workshop series, and numerous participant papers [13-21] in two special sessions of the 2004 AIAA Aerospace Sciences Meeting in Reno, NV

The third workshop [22] retained the DLR-F6 WB from DPW-II as a baseline configuration to provide a bridge to the previous workshop. However, to test the hypothesis that the grid-convergence issues of DPW-II were the direct result of the large pockets of flow separation, a new wing-body fairing was designed to eliminate the side-of-body separation. Details of the FX2B fairing design are documented by Vassberg [23]. The DPW-III was heavily documented with summary papers [24,25], a statistical analysis paper [26] participant papers [27-30], and a special section of the AIAA *Journal of Aircraft*, edited by Vassberg [31-36]. After three workshops, the organizing committee recognized that a recurring theme of the workshop series was related to grid quality and resolution – see Mavriplis et al. [37]

For the fourth workshop [38] a completely new geometry was developed, called the Common Research Model (CRM). The NASA Subsonic Fixed Wing (SFW) Aerodynamics Technical Working Group (TWG), in collaboration with the DPW Organizing Committee, developed the CRM. This wing-body (with and without nacelle-pylons and horizontal tail) configuration is representative of a contemporary high-performance transonic long-range transport. A detailed description of its development is given by Vassberg et al. [39]

The fourth workshop requested grid convergence and Mach sweep computations as in the previous workshops, plus downwash and Reynolds Number studies. Data were submitted from 19 organizations totalling 29 individual datasets. For the grid refinement study, a Richardson Extrapolation methodology [40] was employed to estimate a continuum value for the total drag coefficient. Documentation for these results can be found in summary papers [40-41] and in individual contributing papers [42-56] from two special sessions held at the 28th Applied Aerodynamics Conference in June 2010.

For the fifth workshop [57], which was held in conjunction with the 30th AIAA Applied Aerodynamics conference in June 2012, a new approach was taken with the goal of reducing grid-related errors even further. As with the fourth workshop, the NASA Common Research Model wing body configuration was used for the geometry (without tail). For the grids, a unified baseline [58] family of Multiblock structured meshes was developed with six different levels ranging in size from 0.64×10^6 (Tiny) to 136×10^6 (Superfine) mesh points. Each successive coarse level was derived directly from the finest mesh. Documentation for these results can be found in summary papers [60-61] and in individual contributing papers [62-70] from two special sessions held at the 51st Aerospace Sciences Meeting, January 2013, the 52nd Aerospace Sciences Meeting, January 2014, and a special collection in the AIAA *Journal of Aircraft* [71].

The Sixth Drag Prediction Workshop [72] was held in conjunction with AIAA Aviation 2016. An overview of the computational results, geometry, and grid definitions used for the CRM cases are presented in Ref. 74. Results of a statistical analysis of the grid refinement study are presented in Ref. 75. A detailed description of the static aeroelastic deformation results can be found in Ref. 76. Additional documentation for these results can be found in individual contributing papers in a special collection in the AIAA *Journal of Aircraft* [77-85].

This paper presents an overview of the computational results, geometry, and grid definitions used in the Seventh Drag Prediction Workshop–Expanding the Envelope (DPW-VII) [86]. The workshop was held in conjunction with AIAA Aviation 2022 Conference held in Chicago, Il. and included 18 participant teams from 3 continents representing government, industry, academic, and commercial CFD organizations. The workshop again featured the NASA High Speed CRM model. A primary focus of this workshop was on predicting the effect of shock-induced

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separation on the variation of lift and pitching moment with increasing angle-of-attack at transonic conditions. In DPW-VI only 5 out of 41 solutions submitted adequately predicted this variation [87]. Flow conditions dominated by shock-induced separation represent a significant portion of the flight regime critical to safety and government certification regulations. All too often, anomalies in this flight regime are not discovered until flight test resulting in expensive and time-consuming campaigns to “fix” the issue. Wind tunnels typically cannot simulate the flight Reynolds number and the various aircraft aeroelastic deformations over the range of interest. CFD can contribute if it can be shown to adequately model the development and progression of shock-induced separation with increasing angle-of-attack. The variation of pitching moment with angle-of-attack is a most sensitive indicator in that not only must the lift be adequately predicted but also its distribution with increasing flow separation. This is a sensitive demonstration of CFD accuracy in predicting this critical behaviour. As was done in DPW-VI is the inclusion of the static aeroelastic deformation in the definition of the CRM models for each angle-of-attack/C_L condition specified in the test cases.

2. Geometry and Experimental Data Description

The subject geometry for DPW-VII is the Common Research Model [39] (CRM) developed jointly by the NASA Subsonic Fixed Wing (SFW) Aerodynamics Technical Working Group (TWG) and the DPW Organizing Committee. The CRM was designed as a full configuration with a low wing, body, horizontal tail, and engine nacelles mounted below the wing. For this workshop, only the wing-body configuration was used because the focus was on the wing aerodynamic characteristics. A rendering of the wing-body configuration geometry is shown in Fig. 1, along with a photo of the 0.027 scale wing-body wind tunnel model in the NASA NTF. The CRM was also the subject geometry for DPW-IV through DPW-VI. The supercritical wing is designed for a nominal condition of Mach=0.85, C_L=0.50, and Reynolds Number 40x10^6 based on c_{ref}, which is typical for a full-size commercial transport [39].

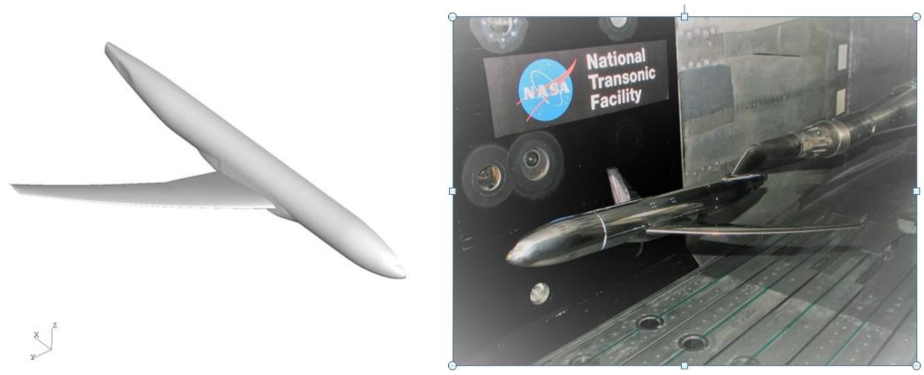

Fig. 1 NASA Common Research Model (CRM) geometry for DPW-VII

An advantageous outcome of the collaborative endeavour sponsored by the NASA Aerodynamics Technical Working Group (TWG) has been that the CRM has now been tested in several facilities thus far, and the data from several of these tests are now publicly available. The National Transonic Facility (NTF) at NASA Langley tested the CRM during January - February 2010, followed by a test at the NASA Ames 11-Foot TWT (Unitary Plan Wind Tunnel 11- by 11-Foot Transonic Wind Tunnel) during March - April 2010. Data from the Langley and Ames tests have been released to the public domain by Rivers and Dittberner [88-90]. The CRM Wing-Body configuration was tested at the European Transonic Wind Tunnel (ETW) facility in February 2014 [91]. These data have also been released to the public domain [92]. These three tests all used the same physical wind tunnel model. A slightly larger version of the CRM Wing-Body-Tail was built by ONERA and tested in the ONERA S1MA wind tunnel [83]. In 2012, an 80% scale model of the NASA CRM built by JAXA was tested in the JAXA 2m x 2m Transonic Wind Tunnel [92].

A comparison of data from the various wind tunnels shows that the wing pressure distributions are virtually indistinguishable at the conditions specified for DPW-VII. Whether this is true for other conditions has not been checked in detail. Force and pitching moment data from the different wind tunnels do differ. It is believed that these differences are mainly due to the corrections applied to the “raw” measured data to account for wind tunnel walls, mounting system, non-uniform flow (buoyancy, upflow, etc.), Mach blockage, lift interference, etc. Each wind tunnel facility tries very hard to determine the “best” set of corrections to its data to simulate “free air”. The CRM test data do not include mounting system corrections. Mounting system effects, which require a special set of “tare and interference” tests to determine, are usually not included in the standard set of corrections applied to the wind

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tunnel data. Computational studies by Rivers, Hunter, and Campbell [94-95] and discussion by Pfeiffer [12] illustrated the magnitude of the mounting system influence on the CRM Wing-Body-Tail configuration. Because of the flow anomalies present in every wind tunnel and the approximate nature of the corrections applied to account for these irregularities, the absolute measurement of forces and moments corresponding to "free air" is impractical if not impossible. It is therefore not unusual that the drag levels will differ between wind tunnels.

Wind tunnel model static aeroelastic deformation has a significant effect at transonic flow conditions. Static aeroelastic deformation has been included in the definition of the CRM models for each angle-of-attack/C_L condition specified in the test cases. The wing static aeroelastic bending and twist deflection were derived using a videogrammetry technique in which the position of markers on the wing was measured during the test. The bending and twist deflection used to define the geometries for DPW-VI were based on data measured in the ETW test in 2014. While the test results from the ETW test and those from the NASA NTF and 11-Foot TWT tests were quite similar, it was decided to use the ETW results. These data were interpolated to the angles-of-attack required in test cases 1 to 6 to define the various geometries [96].

3. Gridding Guidelines and Description of Common Grids

Since the establishment of the Drag Prediction Workshop Organizing Committee in 2000, the DPW-OC has deemed it essential to provide a set of baseline grids on which DPW Participants are to conduct their CFD analyses on workshop test cases. While custom grids are also encouraged, the baseline grids are intended to provide high-quality meshes with a measure of consistency across grid types and family members. In this context, grid types include multiblock, overset, unstructured and hybrid meshes, while a grid family consists of parametrically-consistent meshes of varying grid resolution to be used for grid-convergence studies. Custom grids are encouraged to help bring additional best practices into the public domain to advance the state-of-the-practice in grid generation for RANS simulations. Consistency across baseline meshes is established by use of a set of gridding guidelines (available on the Drag Prediction Workshop website [86].

To satisfy the requirements of all DPW-VII Test Cases, a total of 15 grids per grid type are requested. This minimal set include 8 medium size grids for the aero-elastic (AE) deformations of an Alpha sweep at a low dynamic pressure (LoQ), 1 medium grid at a high dynamic pressure (HiQ), 1 undeflected (NoQ) *medium* grid, and the 6 members of the grid convergence family. Available of the Drag Prediction Workshop website [86] are:

A. Vassberg Grids

A most comprehensive and versatile baseline grid family was provided by Vassberg. As provided, these grids are directly applicable for both multiblock (MB) and overset (OS) RANS flow solvers. In addition, they can be easily converted to fully unstructured hexagons, prisms, or tetrahedra meshes.

B. NLR Grids

Another baseline grid is provided by the NLR. The grid topology of this multiblock structured mesh is more typical of most meshing software than that of Vassberg's grid system

C. JAXA Grids

Baseline hybrid unstructured meshes provided by JAXA were generated using the Mixed-Element Grid Generator in 3 Dimensions (MEGG3D) [97, 98].

E. DLR Grids

DLR's custom-built CFD grids were generated using the commercial grid generation package SOLAR V15.3.8 [99] for building unstructured, hybrid meshes. In the boundary layer mesh predominantly hexahedra-type elements are used, while the farfield mesh is built from tetrahedral elements.

4. Test Case Descriptions

It is recognized that many of the DPW participants are from industry and academia and may have limited time and resources to devote to this type of study. The test case specifications, as with the grid definitions, are set to encourage participation by restricting the number of cases to a manageable number while also providing a challenge to test the state of the art in CFD prediction capabilities. Six test cases were specified for the Seventh AIAA CFD Drag Prediction Workshop, of which, three were optional. A complete description of the test cases is given on the Drag Prediction Workshop website [86].

All CRM simulations are to be "free air" with no wind tunnel walls or support system. The boundary layer is to be modelled as "fully turbulent" for all cases. No free or fixed laminar to turbulent transition is to be specified.

5. Results

The level of participation in DPW-VII was excellent by many counts. Users submitted data from a wide variety of sources, code types, grid types, and turbulence models. Some performed studies that specifically addressed the

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effects of gridding and/or turbulence modelling with the same code. The geometry, test cases, and data format were all uniformly controlled to facilitate the analysis.

A. Participant Descriptions

The Drag Prediction Workshop is open to any individual, group or organization that wishes to perform the calculations according to the specifications set out by the organizing committee. The response for DPW-VII has decreased somewhat from the previous workshop.

A total of 34 datasets were submitted from 18 different teams or organizations. Of these teams, broken down by location and type as follows:

- 7 North America, 7 Europe, 4 Asia
- 7 Government, 3 Industry, 4 Academia, 4 Commercial

The presentations by each participant will be found at the DPW-VII website [86] and contain a description of the computational method used and results presented

All participants were asked to submit forces, moments, pressure, and separation data in the standard format. The large number of datasets poses a challenge in the presentation of the data. Each dataset is assigned an alphanumeric (including Greek) symbol type while colour is used to denote grid or turbulence model type depending on context. All the force/moment and pressure plots below follow the scheme listed in Table 1.

Table. 1 DPW-VII Participants

ID	Sym	Name	Organization	Method	Turbulence Model	Grid Type
A1	A	Mitsuhiro Murayan	JAXA	TAS	SA-noft2-R-QCR2000(Crot=1.0)	CommonHybrid
B1	B	Sansica	JAXA	FaSTAR	SA-R-QCR2000	CommonHybrid
B2	b	Sansica			SA-R	
B3	β	Abe, Hiroyuki			AMM-QCRcorner	
C1	C	David Hue	ONERA	elsA	SA-QCR2000	Block-structured grid
C2	c				kwSST-QCR2000	
D1	D	Ben Rider	Boeing	Overflow v2.3e	SA-RC-QCR2000	Overset
E1	E	Dmitry Kamenetsky	Boeing	GGNS-T1	SA	EPIC
E2	e				SA-QCR2000	
E3	Ε				SA-RC-QCR2000	
F1	F	Rooij, van, Michel	NLR	ENSOLV	EARSMCust	Block-structured grid
F2	f				SST	
G1	G	Krishna Zore	ANSYS	Ansys Fluent	SST-2003	CommonHybrid
G2	g				EARSM	
H1	H	Eliasson, Peter	SAAB/VZLU/FOI	M-Edge	EARSM	CommonHybrid
H2	h				SA	Boeing common multiblock
H3	η				SA	CommonHybrid
I1	1	Frederic Plante, Eric Laurendeau	Polytechnique Montreal	CHAMPS	SA	Overset
I2	i				SA-QCR2000	
J1	J	Thomas Fitzgibbon	FlexCompute	Flow360	SA	CommonHybrid
J2	j				SA-QCR2000	
J3	φ				SA-RC-QCR2000	
J4	Ω				kwSST	
K1	K	Potturi, Amarnatha	Metacomp	CFD++20.1	SARC-QCR	CommonHybrid
L1	L	Shoemake, Lawton	University of Teennesse - Knoxville	Overflow	SA-neg-noft2-RC-QCR	Overset
M1	M	Darbyshire, Oliver	Zenotech	zCFD	SA-neg-noft2	CommonHybrid
N1	N	Pomeroy, Brent	NASA Langley Research Center	Kestrel 12.1	SA-RC QCR	CommJAXACart
P1	P			USM3	SA-R-QCR2000	CommonHybrid
O1	O	Yalu Zhu	Nanjing Xfluids Aerospace Technology Ltd	ASOP	SA-noft2-QCR2013-V	Block-structured grid
Q1	Q	Friedewald, Diliana	DLR (Institute of Aeroelasticity)	TAU	SSG/LRR-ln-omega	CommonHybrid
Q2	q				SA-QCR	
R1	R	Keye, Stefan	DLR	TAU	RSM-ln(w)	CommonHybrid
S1	S	Yannick Hoarau	U-Strasbourg	USMB	SA-QCR	Block-structured grid
S2	s				SST	

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B. Case 1: Grid Convergence Study:

This consisted of a grid refinement study at M=0.85, C_L=0.58, and Chord Re=20 million. As an option, a grid refinement study could also be performed at Chord Re=5 million. The participants were asked to use at least 4 grids of the 6-member baseline grid family for this study. Grids were available for both Reynolds numbers. A standard technique in grid convergence studies is to use Richardson extrapolation [40]. Computational results are plotted versus grid factor, $N^{-2/3}$ (called GRIDFAC in Fig's), where N is the number of solution points. For second order codes, a linear fit should be observed with decreasing error if the refinement is in the asymptotic region. The y-intercept then estimates the theoretical infinite resolution (continuum) result. It is also possible to calculate the convergence rate from this information. This is illustrated in Fig. 2.

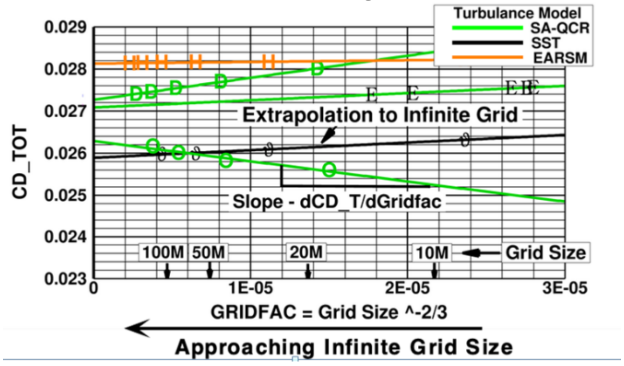

Figure 2. Richardson Extrapolation

Figure 2 shows convergence rate, dCDT/dGRIDFAC, and the drag at infinite resolution for the Chord Re=20 million solutions. These values are shown for each data entry and are ordered by drag at infinite resolutions. Results are identified by the alphanumeric symbol assigned to each data entry and by the turbulence model used (Table 1). in Fig. 3. Not counting the minimum and maximum solutions shown, the average value of the total drag of the Wing-Body CRM is 271.9 counts with a standard deviation of +/- 5.1 counts. This compares with the NTF t215 wind tunnel test value of 284.6 +/- 1.7 counts. Please, be aware that these values should not match exactly due to the different aspects mentioned in previous sections. In addition to other wind tunnel anomalies not modelled in the CFD, the wind tunnel data have not been corrected for the effects of the mounting system! Note that most of the solutions using some form of Spalart-Allmaras turbulence model fell with-in this range. Of these solutions a few showed a convergence rate significantly higher than the norm. Is this due to characteristics of the solver, grid, or both?

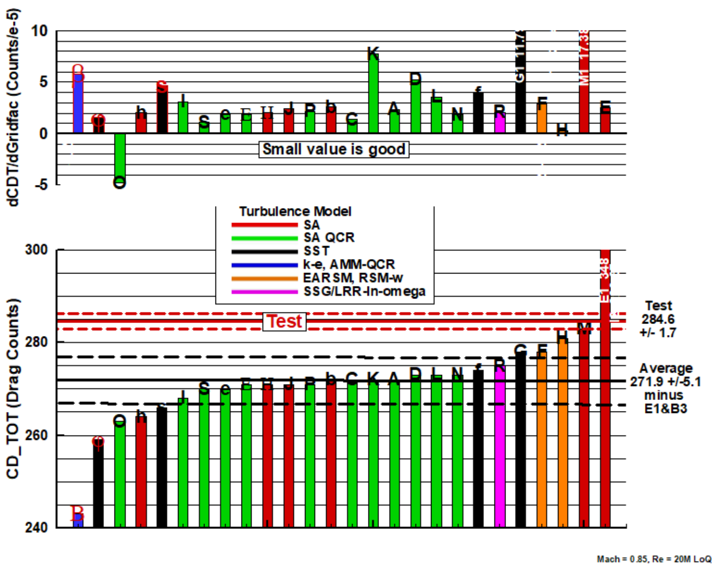

Fig. 3. Case 1a: Total Drag Grid Convergence Sensitivity by turbulence model, M=0.85, CL=0.58, Re=20 million.

Pressure distributions from the finest grid from each solution set submitted for Case 1a, Chord Re=20 million, are shown in Fig. 4. The lift coefficient chosen for these solutions is near the pitching moment break where shock-induced separation is beginning to have some significant. It should not be too surprising that there is little difference

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among all the solutions on the inboard part of the wing. The differences that are seen are mainly in the shock location with the differences increasing on the outboard wing stations. The pressure distributions for Case 1b with a Chord Re=5 million are quite similar. Fewer solutions show less scatter in solutions!

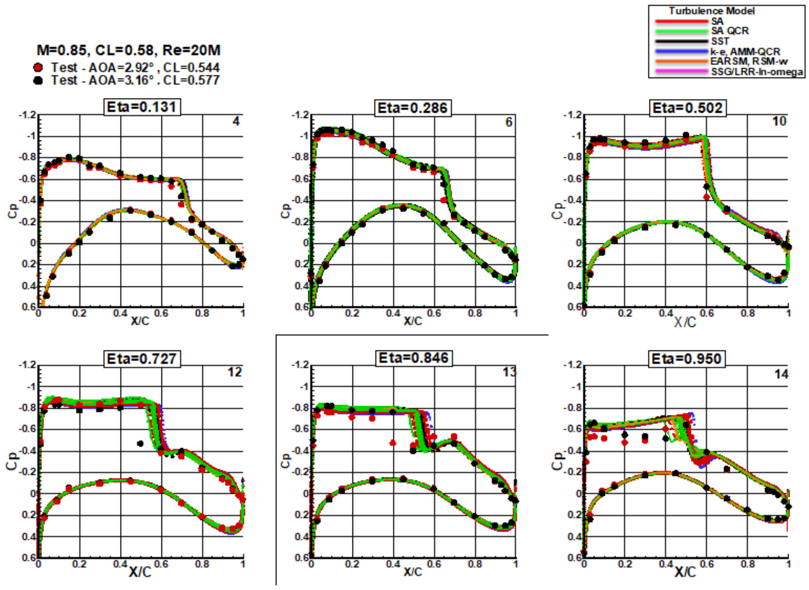

Fig. 4. Case 1a: Wing pressure distributions – All solutions, Finest Grid, M=0.85, CL=0.58, Re=20 million.

Wing section characteristics, lift (normal force) and pitching moment coefficients were requested. These are obtained by integrating the pressure coefficient, Cp, vs. chord fraction, x/c. A Tecplot® Macro script was provided to make these calculations. Unfortunately, the script developed by members of the Drag Prediction Workshop Committee was unable to properly handle some solution formats. Therefore, less than half of the participants have been able to submit these correctly calculated data sets. Wing section characteristics vs. span fraction, eta, are shown for the Case 1a, Chord Re=20 million, in Fig. 5. It is interesting to note that there is very little difference in the section lift characteristics between the any of the solutions. Furthermore, these show excellent agreement with test data on the inboard part of the wing. This is consistent with the results shown in Fig. 4 for the pressure distributions. On the outboard part of the wing the computational results show a higher sectional lift than indicated by the test data. These differences will be discussed in more detail in Section 6 Issues.

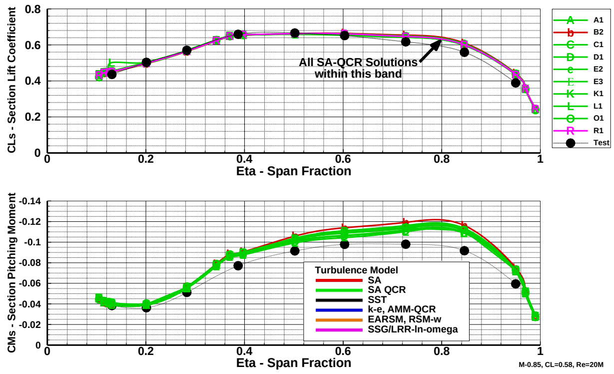

Fig. 5. Case 1a: Wing section lift and pitching moment - all available results – finest grids, M=0.85, CL=0.58, Re=20 million.

The section pitching moment solutions show excellent agreement with test data on the inboard part of the wing. On the outboard part of the wing there is a variation between solutions and a significantly higher section pitching moment compared to the test data. Looking at the pressure distributions in Fig. 4 shows that the spread in section pitching moment on the outboard part of the wing is due to the spread of the shock location between solutions, and the higher values are due the further aft shock location compared to the test data.

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C. Case 2 Alpha Sweep:

The second mandatory CRM case is based on a Wing-Body static aeroelastic/buffet study to investigate the CFD predictions in an angle-of-attack range where significant flow separation is expected. This flight regime is of particular importance to determining aerodynamic loads and stability and control characteristics. Eight angles-of-attack were specified between 2.5° and 4.25° at 0.25° increments. As noted in Section 2, to account for the static aeroelastic deformation of the wind tunnel model, a separate geometry/grid was defined for each angle-of-attack requested. 29 data sets were provided by the Workshop participants for Case 2a, Chord Re=20 million, and 11 sets for Case 2b, Chord Re=5 million.

Lift and pitching moment results from all the Workshop submittals, along with the NTF test data are shown in Fig. 6 for Case 2a, Chord Re=20 million. Most of the solutions are clustered within a "fan" that gets progressively wider with increasing angle-of-attack. In general, the solutions are indicating a higher lift at a given angle-of-attack, and a more negative (nose down) pitching moment at a given lift coefficient than indicated by the test data. Some of this level difference could be due to the lack of mounting system corrections to the wind tunnel data, but not of the order shown.

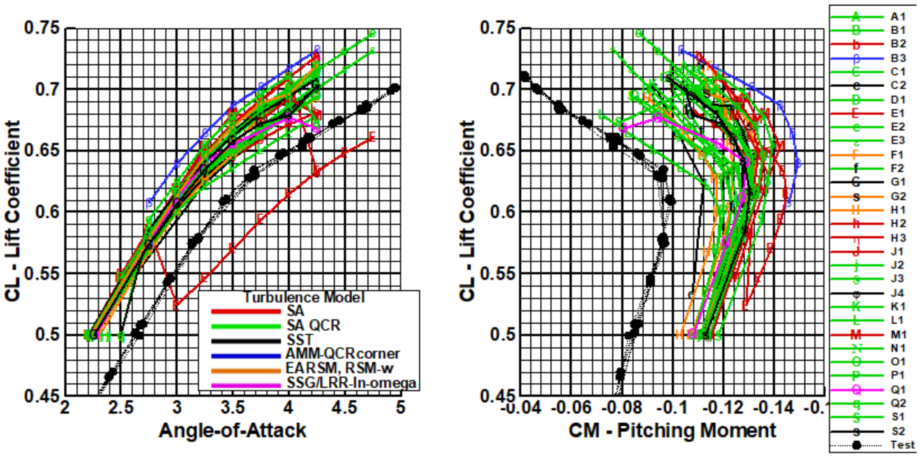

Fig. 6. Lift and pitching moment for all solutions, M=0.85, Re=20 million.

Pressure distributions at select wing eta stations at an angle-of-attack of 4.25° are shown in Fig. 7. Several solutions exhibited a large side-of-body separation bubble with increasing angle-of-attack whose effects could be seen in the wing pressure distributions, and in the force and moment data. The wind tunnel data do not exhibit any evidence of flow separation on the inboard portion of the wing (first row of pressures located at BL=151), nor does it show an early lift break. Also evident in the pressure distributions is the large spread of the shock location on the outboard part of the wing. This spread in computed shock location is largely responsible for the fanning out of the lift and pitching moment solutions as angle-of-attack is increased.

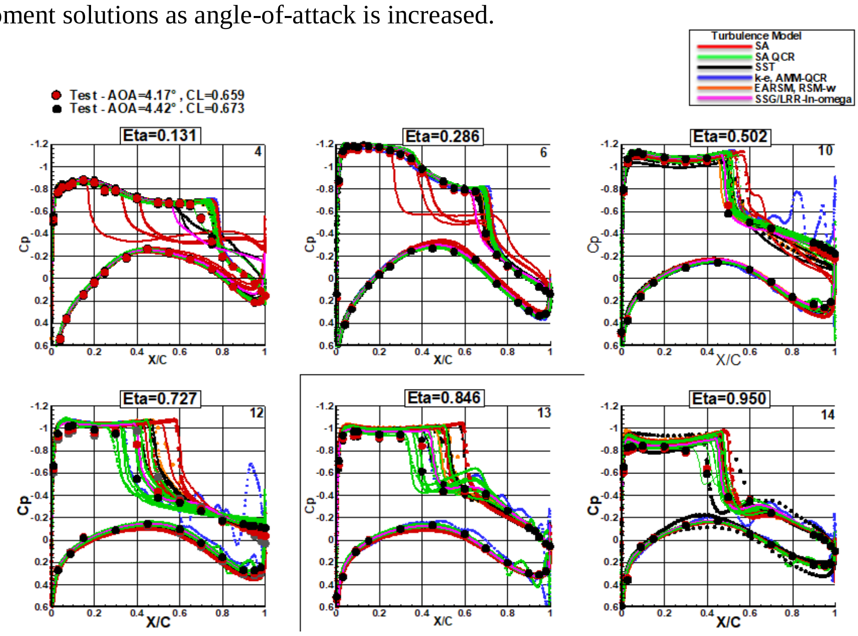

Fig. 7 Pressure Distributions – 4.25° angle-of-attack, M=0.85, Re=20 million.

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D. Case 3: - Reynolds Number Sweep at Constant CL

Case 3 called for a Reynolds number sweep at a constant lift coefficient. For this case the lift coefficient chosen, CL=0.50, is representative of a cruise condition. Ideally this sweep from Chord Re=5 to 30 million would be done at a constant dynamic pressure as well at the constant lift coefficient. Unfortunately, the limitations of the cryogenic wind tunnels prevent this. Instead, Chord Re=5 and 20 million conditions were run at a "low" dynamic pressure, and Chord Re=20 and 30 million conditions were run at a "high" dynamic pressure. This allows the separation of Reynolds number effects and dynamic pressure (static aeroelastic) effects. Participants were provided with geometries and grids appropriate for those conditions.

Reynolds number and dynamic pressure increments are shown in Fig. 8 for the computed and experimental results. The experimental increments are based on data from two campaigns in the NTF for the Wing-Body configuration. In addition, experimental increments are also shown from data taken in the ETW wind tunnel for the Wing-Body-Tail configuration. The presence of the tail should not affect the increments at these conditions. Increments are shown for: Reynolds change at LoQ (~1380 psi) – Chord Re=20 – 5 million; Dynamic pressure change at constant Chord Re=20 million – HiQ (~1980 psi) – LoQ (~1380 psi); Reynolds number change at HiQ (~1980 psi) - Chord Re=30 - 20 million. Computational increments are shown in index order and are coloured by turbulence model type. The computation increments are consistent and of the same order as the test increments. There is little difference in choice of turbulence model at benign flight condition. As Case 2 suggests, this will not be the case at more extreme conditions with significant flow separation.

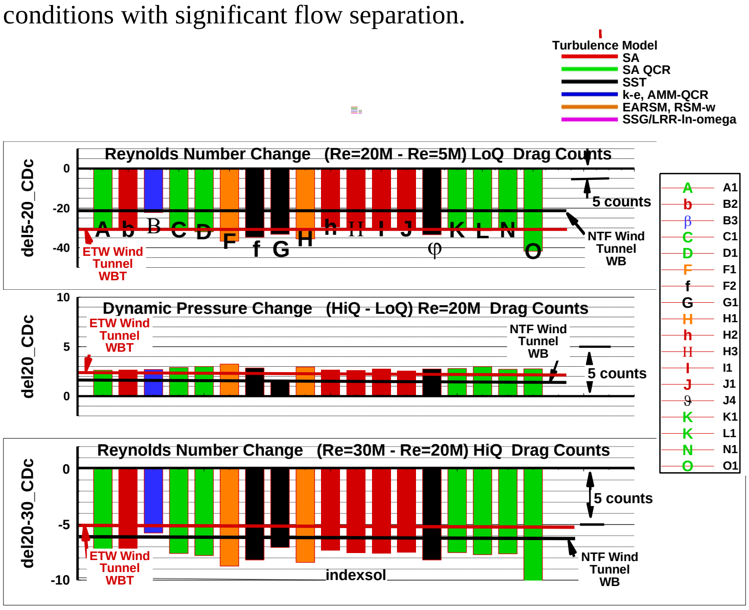

Fig. 8. Reynolds Number Sweep at Constant CL=0.50

E. Case 4: - Grid Adaptation [Optional]

New to DPW-VI was the request for grid adaptation solutions of the CRM Wing-Body configuration as an optional case. A similar request is made in DPW-VII but at a higher fixed lift, C_L=0.58. In addition to the fixed lift case an angle-of-attack sweep like Case 2 was also desired. Unfortunately, only four solution sets were provided by two organizations. Three solutions were based on GGNS-TI using the same adaptation technique but differed in the version of the Spalart-Allmaras turbulence model. GGNS-TI employs 2nd-order node centered SUPG finite-element discretization with a strong solver that achieves machine precision residual convergence [100]. It employs the EPIC (Edge Primitive Insertion Collapse) adaptive grid tool [101] focusing on a sizing metric derived from the Mach Hessian or Entropy Adjoint error. GGNS-T1 started with a small grid of about 16,000 cells and ended up with about 13.5 million cells after 22 to 24 iterations. The fourth solution Kestrel [102], employs HLLE++ and LDD+ viscous flux with 2nd order spatial and temporal accuracy. Initial grids used the committee provided JAXA unstructured/Cartesian grids.

The four solutions are included with the fixed solutions of Case 1 and 2 in Figs 3 to 7. The adaptive grid solutions tend to have the characteristic of a sharper definition of the shocks. Little benefit is seen for adaptive grid solutions compared to fixed grid solutions for this geometrically simple wing-body geometry. The resultant grids may be smaller, but the work required to obtain these solutions can be several times greater than that required for a fixed grid solution. The promise that solution adaptive grids bring is that they should be able to deliver a consistent

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set of solutions for configurations, and/or conditions for which prior gridding experience may not be available. Even for this configuration, the "optimum" grid distribution will change dramatically for a drag rise series ranging from Mach = 0.70 to 0.90. Decades have been spent developing and validating gridding guidelines for these "simple" geometries and expected flow features. Additional work remains to be done to bring this technology to a "production" capability for 3-D RANS. It is a technology that needs to be matured.

F. Case 5 - Beyond RANS [Optional]

Solution technologies beyond steady RANS such as URANS, DDES, WMLES, Lattice Boltzmann, etc. were sought for DPW-VII. Unfortunately, insufficient information was available to draw any firm conclusions.

G. Case 6 - CRM WB Coupled Aero-Structural Simulation [Optional]

The purpose of Test Case 6 is to compute a steady aeroelastic equilibrium state for M = 0.85; CL=0.58, Re = 20 million. Unlike with the other DPW-VII test cases, only the undeformed jig shape geometry of the wing is provided. Links to the structural description of the wind tunnel model are available on the Drag Prediction Workshop website [86]. Here, the flight shape is the result of the coupled simulation. Unfortunately, only two participants have submitted data for this optional case. Therefore, this summary will only consist of a brief comparison of results and not include any statistics.

A common approach to static aeroelastic simulations is the simultaneous interaction between the outer flow field and the flexible aircraft structure in a closed coupling loop. This loop includes solvers for CFD and Computational Structural Mechanics, indicated here as CSM. Coupling between CFD and CSM is implemented through interpolation algorithms for aerodynamic forces and structural deflections. The simulation starts by computing an initial CFD solution on the undeformed mesh and proceeds until convergence is reached. The method of interpolating aerodynamic forces to the structural domain and performing a static analysis to compute deflections is usually called a *direct* coupling approach. It was used by both participants. In Fig. 9 the spanwise bending and twist deformation results from both participants are plotted in comparison to experimental data from the Trans National. Access test campaign at the European Transonic Wind Tunnel (ETW) in Cologne, Germany [91]. It should be kept in mind that all deformations shown here relate to the wind tunnel model scale which is 2.7% of the full-size CRM. The measured deformation, represented here by black symbols, was also used to derive the aeroelastically pre-deformed wing geometries for the other DPW-VII test cases. The blue line is almost curve fitting the test data, while the red line over-predicts bending by about 10%. For the aerodynamically more relevant twist deformation both participants predict the measured data accurately with less than 0.1% deviation. Both results lie within the measurement accuracy, indicated here by black error bars. Similar results were found for other angles-of-attack.

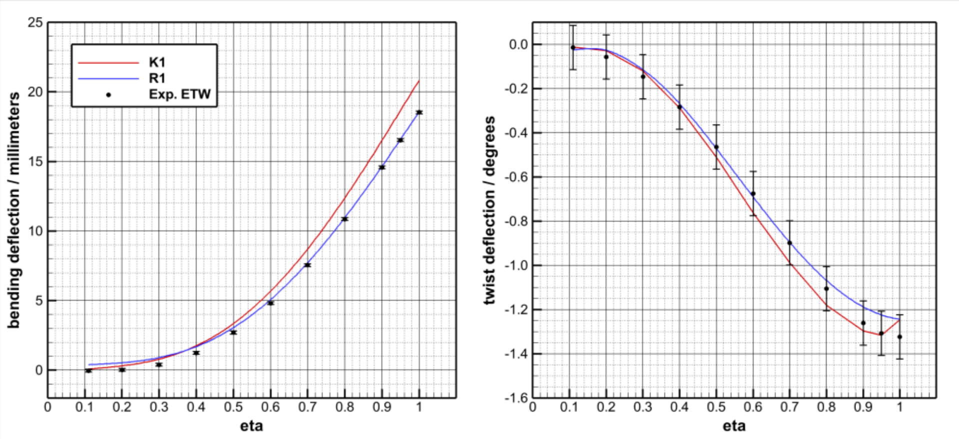

Fig. 9. Wing bending and twist deformations at CL = 0.58.

The wing static pressure distributions were essentially the same as shown in Fig. 4 in comparison to results from other DPW test cases that require pre-deformed wing geometries. Both participants' methods are capable of correctly predicting wing deformations and static pressure distributions under varying aerodynamic loads.

6. Issues

An important goal of the DPW series of workshops is to identify significant issues/shortfalls in need of further CFD development. DPW-VII highlights continuing issues that, while seeing some progress over the years, continue to plague the state of CFD and experiment. More detailed information about how the experimental data were generated is needed to better validate the CFD, and to provide the detailed information necessary to improve the turbulence models and decide whether unsteady simulations are necessary.

DOI: 10.13009/EUCASS2023-055

A. Premature Side-of-Body Separation

The prediction of premature side-of-body separation continued to plague some simulations. At the design condition of M=0.85, C_L=0.50, where we can expect little or no flow separation, this is not an issue. However, as angle-of-attack is increased, some solutions did exhibit excessive side-of-body separation as defined as an adverse pressure distribution influence at the first row of pressure taps on the wind tunnel model wing (located at BL=151

The use of the quadratic constitutive relation (QCR) in the SA or SST turbulence model eliminates the premature separation. In addition, two equation turbulence models, the RSM-ln(ω), SSG/LRR-ln-ω. kωSST, kωSST-QCR2000, AMM-QCRcorner and EARSM, turbulence models did not show any evidence of premature SOB separation. Premature side-of-body separation was much less of an issue in DPW-VII than experienced in previous workshops. This type of 3D corner flow separation continues to receive more attention in turbulence model development and CFD application, e.g., the comprehensive NASA Juncture Flow Experiment [103,104].

B. Excessive Aft-Loading

Another ongoing issue can be seen in Fig. 7 for lift and pitching moment and in Fig. 6 for wing sectional lift and pitching moment distributions. The section lift and pitching moment solutions show a lift higher than experiment and pitching moment more negative than experiment on the outer portion of the wing. This might partially be explained by the lack of corrections to the experimental data for the upper swept sting support to the wind tunnel model. These corrections require a special set of wind tunnel tests using different mounting systems to the model. These tests were not carried out for the CRM in any of the wind tunnel campaigns. Computational studies [89, 94, 95] on the impact of the mounting system show that its effect will be to reduce lift and reduce the nose-down pitching moment. However, the wing pressure distributions do offer a clue. Pressure distributions around the wing trailing edge from all the available solutions submitted at the M=0.85, C_L=0.58 and from the comparable test data are shown in Fig. 10. As long as the flow is attached, these distributions vary little over the range of conditions of interest. The pressure coefficient values on the upper surface of the wing are consistently lower (more negative) than those of the test data. Similarly, the values on the lower surface of the wing are consistently higher (more positive) then those of the test data. The difference between the upper and lower surface represents lift and contributes to negative section pitching moment. These differences become more aggressive the further outboard on the wing. This is seen in Fig. 5 in the spanwise sectional lift and pitching moment characteristic. The CFD sectional data match the experiential data well on the inboard part of the wing but predict higher lift and more negative pitching moment on the outboard part of the wing. This excessive "aft loading" is seen from every turbulence model, gridding scheme, and solver type presented in this workshop. It is highly unlikely that this excessive "aft loading" is due to experimental issues. The computational results of pressure distribution, and forces and moments, are self-consistent. In the wind tunnel test, the instrumentation is completely independent. The geometry of the wind tunnel model has been validated. The nearly solid nature of the wing minimizes any chordwise aeroelastic effects. This excessive "aft loading" prediction has also been seen on other wind tunnel models with significant trailing edge camber. While progress has been made with the premature SOB separation, the question of the excessive "aft loading" remains an issue, needs further investigation.

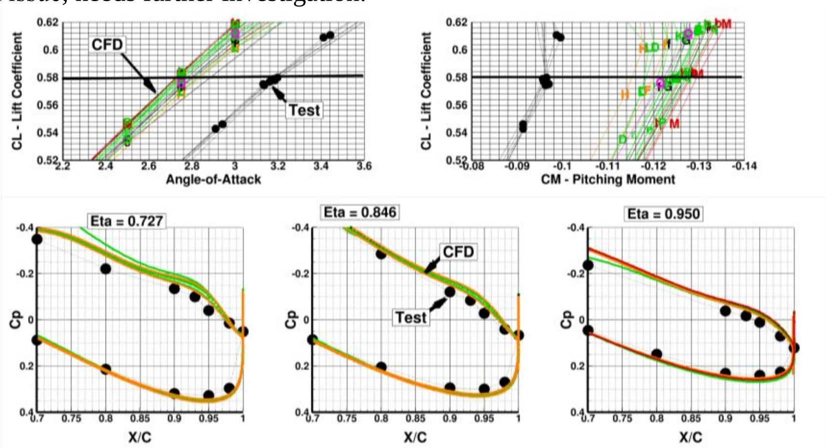

Fig. 10"Excessive Lift" - Force and Moment and Trailing Edge Wing Pressures at M=0.85, CL=0.58, Re=20 million – All Solutions.

DOI: 10.13009/EUCASS2023-055

C. Solution Spread

In addition to the "aft-loading" issue, Fig. 6 also shows that the spread in lift at a given angle-of-attack and the spread in the pitching moment at a given lift coefficient increases with increasing angle-of-attack and lift coefficient, respectively. This "spread" is in addition to the level changes caused by the excessive "aft loading." Looking at the wing pressure distributions at the outboard most three wing stations shown in Figs, 4 and 7 provides a clue for the increasing spread. Fig. 7 shows pressure distributions at 4.25° angle-of-attack. Note the large variation of shock location from these solutions. Shock location is largely driven by shock-induced separation at this condition. Compare this to the tight spread of shock locations shown in Fig. 4 from all solutions at C_L=0.58, where there is little or no shock-induced separation. Each one of these solutions on its own appears to be a valid solution, yet as angle-of-attack increases so does the spread of shock location on the outboard portion of the wing which is driven by the details of shock-induced separation.

We know that in a well-executed wind tunnel or CFD campaign we can have greater confidence in "deltas" rather than in absolute levels. We can have greater confidence in the variation of lift and pitching moment with the variation with angle-of-attack. By adding a constant value (different for each solution) to angle-of-attack and pitching moment to each solution to match the values of the average of NTF test data at a CL = 0.53, the CFD solutions can be collapsed around the experimental data as shown in Fig. 11 for Chord Re=20 million. The value of CL = 0.53 was chosen to encompass all the submitted solutions at a condition where the flow should be free of shock-induced separation. The figure clearly shows the variation of lift and pitching with increasing angle-of-attack. Note that the solution spread starts at around CL = 0.61 or between 3.0° and 3.25° angle-of-attack for Re=20M. This represents the beginning of significant shock-induced separation. At 4.25° angle-of-attack, the spread in lift and pitching moment is large. While this approach is somewhat unorthodox, it does allow a better assessment the behaviour of lift and pitching moment with increasing angle-of-attack.

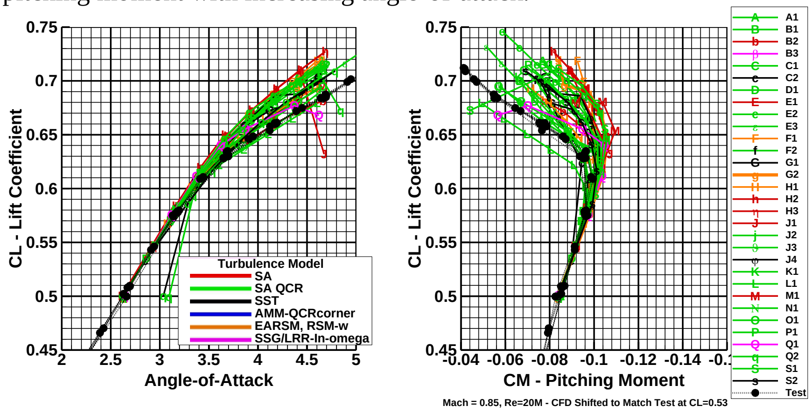

Fig. 11. Lift and Pitching Moment Shifted to Match Experiment at CL = 0.53, Chord Re=20 million.

Eliminating (pruning) solutions that deviate from the test data at the higher lift coefficients leaves a small number of solutions that best match the experimental data, shown in Fig. 12. Also shown in this figure by the dashed lines are the limits of the spread of CFD solutions. For the Case 2a (Chord Re=20 million) only five out of 34 solutions match test data well up until a lift coefficient of 0.65. All five solutions used a variation of the SA with QCR turbulence model. Two (D1, O1) used a structured multiblock or Overset grids. The other three (E3, J2 and K1) used an unstructured hybrid type grid – see Table 1.

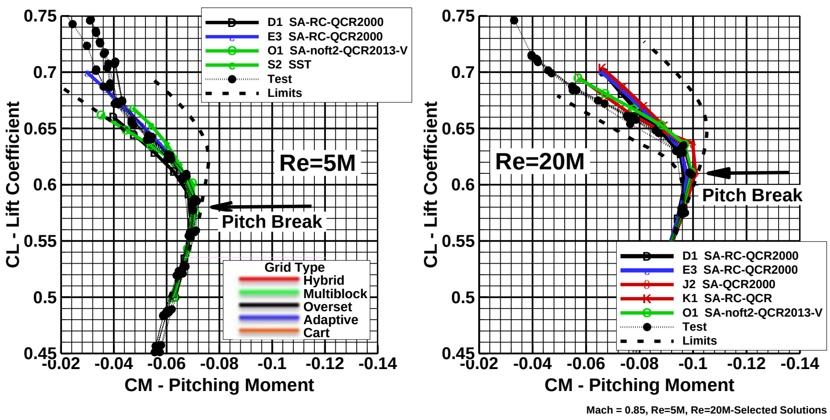

Fig. 12. Selected Lift and Pitching Moment Solutions that Best Match Experiment, Chord Re=20 and 5 million.

DOI: 10.13009/EUCASS2023-055

For the Case 2b (Chord Re=5 million) four out of 11 solutions matched the experimental data quite well. Three (D1, E3, and O1) used a variation of the SA with QCR turbulence model. The fourth (S2) used some version of the SST turbulence that was not further identified. In terms of grid type three (D1, O1, S2) used a structured multiblock or Overset grid. The other (E3) used an adapted unstructured hybrid type grid. Results from shifted solutions D1, E3, and O1 best matched the experimental force and moment data for both Chord Re=20 million and 5 million.

Further investigation looked at the wing pressure distributions and consistent with the force data these same solutions exhibited the best agreement with the pressure distributions and section lift and pitching moment distributions. One must ask why other solutions using different solvers but essentially the same grids and turbulence models did not. Subtle differences between solver, grid, and turbulence model seem to make large differences in shock-induced separation and the resulting forces and moments.

7. Observations and Concluding Remarks

The Seventh Drag Prediction Workshop – "Expanding the Envelope" was held in conjunction with AIAA Aviation 2022 conference in Chicago, Il. The event was well attended by a diverse group of expert CFD practitioners from three continents representing government, industry, academia, and commercial code development institutions. 18 teams contributed results. This workshop focused on several studies of the NASA Common Research Model, High Speed CRM wing-body configuration. These included single point grid convergence and drag increment, high angle-of-attack static buffet conditions, optional grid adaptation, optional "Beyond RANS" and optional coupled aerostructural studies. This paper covers the key results from the workshop.

A primary focus of this workshop was on predicting the effect of shock-induced separation on the variation of lift and pitching moment with increasing angle-of-attack at transonic conditions. Flow conditions dominated by shock-induced separation represent a significant portion of the flight regime critical to safety and government certification regulations. All too often, anomalies in this flight regime are not discovered until flight test resulting in expensive and time-consuming campaigns to "fix" the issue. With sufficient accuracy, reliability, and robustness CFD may help avoid these surprises. The variation of pitching moment with angle-of-attack is a most sensitive indicator in that not only must the lift be adequately predicted but also its distribution along the span of the wing with increasing flow separation. This is a sensitive demonstration of CFD accuracy in predicting this critical behaviour. As was done in DPW-VI is the inclusion of the static aeroelastic deformation in the definition of the CRM models for each angle-of-attack/C_L condition specified in the test cases. The inclusion of wing aeroelastic deformation at transonic conditions is essential for accurate CFD predictions. These deformations can be based on measurements taken during a test or on coupled aero-structural simulations.

A total of 34 datasets for the CRM cases were provided on structured, overset, and unstructured grids. One team provided solutions using the same solver and turbulence model but with different grids. Many provided solutions using the same solver and grid but with different turbulence models.

The Case 1 Wing-Body grid convergence study showed similar results to those in DPW-VI but for a higher lift coefficient with stronger shocks. This higher lift coefficient was chosen to challenge the codes at a condition close to the start of the pitching moment break characteristic of the development of significant shock-induced separation. The solutions exhibited a "tighter" convergence of total drag to the continuum with a spread of less than 10 drag counts. Considering that this was a more challenging condition than specified in DPW-VI results here indicate increased robustness in CFD since 2016.

Predicting the effect of shock-induced separation on the variation of lift and pitching moment with increasing angle-of-attack at transonic conditions was addressed by Cases 2, and 4, and to some extent 5 and 6. Case 5 results were limited and not considered adequate for this evaluation. As angle-of-attack is increased the number of outliers observed to have uncharacteristically large wing trailing edge separation at the side-of-body was greatly reduced compared to that seen in DPW-VI. Solutions identifying as only SA and SST turbulence models were most susceptible to the premature side-of-body separation. Experience has shown that premature separation with these turbulence models is very sensitive to gridding details in the wing-body junction region. The use of the quadratic constitutive relation (QCR) in the SA or SST turbulence model is shown to eliminate the premature separation. In addition, solutions using the two-equation turbulence models did not show any evidence of premature side-of-body separation up to at least 4° angle-of-attack.

All the solutions indicate a higher lift at a given angle-of-attack, and a more negative (nose down) pitching moment at a given lift coefficient than observed in the test data. The primary cause appears to be due the excessive "aft loading" predicted by all the submittals. This excessive "aft loading" has been seen on other wind tunnel models with significant aft wing camber and deserves further study.

For Cases 2, 4, and 6, the lift and pitching moment results are clustered within a "fan" that gets progressively wider with increasing angle-of-attack. Each one of the solutions on its own is considered a valid solution, yet as angle-of-attack increases so does the spread of shock location on the outboard portion of the wing. Collapsing the

DOI: 10.13009/EUCASS2023-055

computational results to match test data at an attached lift condition allows an assessment of the development of shock-induced separation and its effect on lift and pitching moment as angle-of-attack is increased. Only 5 of the 34 solutions submitted for the Re=20 million condition closely matched test data. Three of the same (solver, grid type, turbulence model) also closely matched test data for Re=5 million.

New to DPW-VII Case 3 involved calculating a Reynolds number spread from Chord Re=5 million to 30 million at a constant lift coefficient representative of cruise flight. The computation increments were consistent and of the same order as the wind tunnel test increments. There is little difference in choice of turbulence model at this benign flight condition. This will not be the case at more extreme conditions with significant flow separation.

Case 4 requested grid adaptation solutions of the CRM Wing-Body configuration as an optional case. This is an active area of CFD research, and it was time to take another measure of the progress. Four solution sets were provided by two organizations. Three of the solutions exhibited a strong convergence to the same drag level in the continuum as the fixed grid solutions. The wing pressure distributions from these solutions are essentially indistinguishable from those of the carefully crafted fixed grid solutions but with the characteristic of a sharper definition of the shocks. The promise that solution adaptive grids bring is that they should be able to deliver a consistent set of solutions for configurations, and/or conditions for which prior gridding experience may not be available. Additional work remains to be done to bring this technology to a “production” capability for 3-D RANS. It is a technology that needs to be matured.

Case 5 requested solution technologies beyond steady RANS such as URANS, DDES, WMLES, Lattice Boltzmann, and other scale-resolving schemes. As only two participants submitted data to the workshop, no significant conclusions could be made from the limited data presented. Numerous participants investigated this case and presented results (not yet available for the workshop in 2022) at the AIAA 2023 SciTech Special Session [105,106].

Case 6 requested coupled aero-structural simulations for the second time during the DPW series. The effects of static aeroelastic twist and bending can be very significant at transonic flow conditions. The inclusion of static aeroelastic deformation of the CRM wind tunnel model in the previous DPW-VI attests to their importance. Only two teams submitted solutions in DPW-VII. Participants data show some differences in wing bending deformation, but a good agreement for twist. Accordingly, the resulting wing pressure distributions show a very good agreement over the entire wing, for all angles-of-attack, and were essentially identical to those from the other test cases.

Important issues were raised in this and in previous workshops that point to the need for continuing CFD and experimental research. Previous studies of the influence of the mounting system on the wind tunnel model focused only on the Wing-Body-Tail model. A new CFD study of the CRM wind tunnel mounting system effects is needed. This study should include the effects on the CRM Wing-Body, Wing-Body-Tail, and Wing-Body-Nacelle-Pylon configurations. Excessive “aft loading” was seen from every turbulence model, gridding scheme, and solver type presented in this workshop. It is highly unlikely that this excessive “aft loading” (also seen on other wind tunnel models with significant aft wing camber) is due to experimental issues and more likely a turbulence modeling issue that needs further attention. The wide spread of lift and pitching moment in the CFD solutions at the high angles-of-attack is driven by the predicted shock-induced separation and resulting shock location. The shock location variation at these high angles-of-attack may be physical as well as computational. At 4°, the wind tunnel model experiences a significant amount of buffet. The wind tunnel forces, moments, and pressure data typically represent “average” steady results, but how steady is the flow at these conditions? Is the shock location across the wing steady or moving back and forth? On the CFD side, one must ask if steady Reynolds-Averaged Navier-Stokes (RANS) is adequate for modeling this flow regime in case that unsteady phenomena potentially occur. If the shock movement is small (less than a few percent chord) then RANS is probably adequate. If so, what was it of the five out of 34 solutions that matched the force and pressure data better than the other solutions, many of which used the same grids and turbulence models? These are CFD details that are not well understood. If unsteady shock movement is greater than a few percent chord, will URANS (Unsteady Reynolds Averaged Navier-Stokes) be adequate, or must one go to an eddy-resolving method such as DES (Detached Eddy Simulation) to accurately simulate this flow regime? Additional detailed wind tunnel data, if not already available, is needed to help quantify this issue and to support an improvement of turbulence models, potentially needs for data reinforced models. The magnitude of the unsteady shock movement on the CRM wind tunnel model could be resolved by use unsteady pressure sensitive paint (uPSP) [107]. Answers are necessary to rely on CFD for “Expanding the Envelope.”

It is obvious from this and prior workshops that there is an interaction between solver, grid, and turbulence model that becomes most prevalent when there is significant shock-induced separation that we don’t understand. These solution sets and experimental data represent a gold mine of information to further the knowledge of CFD and aerodynamics – a great source for graduate student projects. A more detailed summary report on the 7th Drag Prediction Workshop can be found in Ref. 108. Furthermore, a detailed report encompassing past DPW-IV, DPW-V, and DPW-VI workshops can be found in Ref. 109.

DOI: 10.13009/EUCASS2023-055

Acknowledgments

We would like to thank Tecplot for their support throughout the Drag Prediction Workshop Series, as well to other similar CFD workshops.

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