AIAA CFD DRAG PREDICTION WORKSHOP: AN OVERVIEW

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Abstract

An overview of the American Institute of Aeronautics and Astronautics Computational Fluid Dynamics Drag Prediction Workshops (AIAA CFD DPW) is presented. The DPW vision statement and format, which has contributed to its success and international participation, will be examined. The geometry and results of the first three workshops will be reviewed, and the subject of future workshops will be discussed.

1 Introduction

The Applied Aerodynamics Technical Committee (TC) of the American Institute of Aeronautics and Astronautics (AIAA), an ICAS member society, has sponsored a series of computational fluid dynamics (CFD) drag prediction workshops (DPW) over the last five years. The goal of these workshops is to assess state-of-the-art computational methods as practical aerodynamic tools for aircraft force and moment prediction of industry relevant geometries, focusing on drag prediction.

The idea of DPW came about from members of industry who were routinely using CFD in the design and development of aircraft and wanted to improve the credibility of CFD to the non-CFD community. The supposition of these individuals was that the scatter band associated with CFD force and moment predictions would be smaller than the scatter band associated with wind tunnel derived data. A transonic wing-body transport configuration was identified, for which the geometry is publicly available and for which wind tunnel data from three different test facilities has been published. A standard set of computational structured, unstructured and overset grids were generated using common resolution guidelines, and these were given to individuals participating in the workshop, so that force and moment variability attributed to differences in computational grids could be minimized. Participants were asked to submit CFD predicted results for a set of specified test cases which included a single point fixed-lift condition, drag polars, and constant-lift drag rise curves. Finally, statistical techniques were employed to quantify the CFD predictions. It was found that the code-to-code scatter of the force and moment predictions was more than an order-of-magnitude larger than anticipated. The CFD predictions exhibit a 2-sigma confidence interval of roughly +/- 40 counts of drag (1 count of drag corresponds to a coefficient of drag (C_D) change of 0.0001), whereas the experimental data exhibits a 2-sigma confidence interval of roughly +/- 8 drag counts [1]. Instead of convincing the non-CFD community of the accuracy of modern CFD methods the results of the first DPW (DPW 1) demonstrated a severe deficiency in Reynolds-Averaged Navier-Stokes (RANS) CFD force and moment predictions.

Despite the fact that the results of DPW 1 did not achieve the organizers original intent, it was considered an overwhelming success. It brought together CFD developers and practitioners and focused their efforts on a common problem. It facilitated an exchange of learned best practices and promoted open discussions, identifying areas requiring further research or additional scrutiny. For the first time, it employed rigorous statistical analysis to objectively assess CFD results. Finally, it revealed to the CFD and applied aerodynamics communities that state-of-the-art CFD methods are insufficient for force and moment predictions.

The intense interest generated by the first drag prediction workshop (DPW 1), as well as the unexpected results and the questions that it raised, naturally led to a second drag prediction workshop (DPW 2) and subsequently to a third (DPW 3). This paper is an overview of the AIAA CFD DPW series and is intended to familiarize the reader with the structure, focus and results of the workshops. Readers interested in further details about the workshops or individual CFD studies concerning DPW test cases are referred to the publication list included in this paper. In addition, DPW information, workshop presentations, wind tunnel data, computational results, downloadable geometry and computational grids can be found at the following URL address: http://aaac.larc.nasa.gov/tsab/cfdlarc/aiaa-dpw/, which can be assessed via the AIAA Applied Aerodynamics TC website located at: http://www.aiaa.org/tc/apa/apatc.html.

2 The Workshops

Each of the three workshops that have been held to date has maintained the same three objectives. These are:

1. Assess state-of-the-art computational methods as a practical tool for aircraft force and moment predictions of industry relevant aircraft geometry, focusing on drag prediction.
2. Provide an impartial forum for evaluating the effectiveness of existing computer codes and modeling techniques using Navier-Stokes solvers.
3. Openly identify and discuss areas needing additional research and development.

Furthermore, the continued success of the workshop series and the positive feedback given by workshop participants has incited the workshop organizing committees to maintain a consistent format for the two day workshops. This format is made up of the following elements:

- Common subject geometry. Subject geometries are chosen that are simple enough that high quality computations can be performed but are still relevant to the type of configurations useful to industry. A further criterion of the subject geometry is that it must be publicly available. Finally, the existence of high-quality, publicly available wind-tunnel data associated with the geometry is desired.
- Required and optional test cases. Several test cases are chosen for comparison of the CFD results. Required test cases typically involve a single-point fixed-lift condition and drag polars. Optional test cases typically include other information interesting to industry, such as constant-lift drag rise curves or delta drag computations of two similar configurations. Specific test conditions (e.g. Mach number, lift, Reynolds number) are typically dictated by the conditions at which wind tunnel experimental data was obtained. In this way, the CFD results can be directly compared to the wind tunnel data. For each test case condition, participants are asked to submit coefficient of lift (C_L), coefficient of drag (C_D) and pitching moment coefficient (C_M) values. In some instances wing pressure coefficient (C_P) distributions are collected.
- Standard set of provided grids. A standard set of grids is provided to encourage participation and reduce variability in the CFD results. Multi-blocked structured, unstructured and overset grids are generated using guidelines established by the DPW organizing committee and are posted on the DPW website for download. Participants are asked to use the provided grids, if at all possible, for the single-point fixed-lift required test case, but are encouraged to generate their own grids using best-practice techniques for other test case computations. The DPW

committee has implemented the policy that all grids used to compute data for the workshop must be made publicly available via the DPW website.

- Rigorous statistical analysis. A statistical analysis of the CFD results is performed to establish confidence levels in the data. Because of the importance of this element to the success and interest in DPW and because of its uniqueness, as compared to other CFD comparison studies, it is described separately in greater detail below.
- Participant presentations. Attendees who submit CFD results are given the opportunity to present their results and modeling techniques at the workshop. The submittal of full-papers is not a requirement for DPW. However, participants reporting interesting, novel and exceptional work are often invited to present full-papers at DPW special sessions during the AIAA Aerospace Sciences Meeting held annually in January.
- Open forum sessions. Several open form sessions are scheduled during the workshops to encourage discussion and interaction among participants and attendees.

Overviews of the three workshops are given below, following a brief description of the statistical approach central to the analysis of the DPW data. The overviews do not describe in detail the geometry or test cases performed in each workshop. Neither do they present comprehensive lists describing the submitted data (e.g. flow solvers used, grid specifications, turbulence models, etc.). Readers interested in this level of detail are referred to the data summary and statistical analysis papers [1-7] and to the DPW website [8].

2.1 Statistical Approach

The statistical approach used to assess the DPW computational results is known as N-Version Testing [9] and is akin to the N-th Order Replication [10] measurement process. In this process, no individual computational prediction (outcome) is considered the "correct" answer. Instead, the analysis aims at quantifying the reproducibility of the data. The analysis examines the scatter (dispersion) associated with the collection of CFD predictions.

Each predicted quantity (e.g. drag) is obtained via an individual computational process. All of these processes together form a collective computational process. The scatter of the DPW results is considered to be the noise in that collective computational process that results because of varying conditions of measurement. The changed conditions of measurement for DPW is the different codes, solution methods, turbulence models, grids, computing platforms, observers (those who performed the computations) and so on. This statistical approach is consistent with the new international standard for reporting measurement uncertainty [11]. Details of the approach can be found in Ref [6].

2.2 DPW 1

DPW 1 was held at Anaheim, California in June 2001 in conjunction with the 19th AIAA Applied Aerodynamics Conference. About forty-five persons were in attendance for the two day workshop. A total of 18 international participants using 14 different codes submitted data and presented results at the workshop.

The subject geometry of DPW 1 is the DLR-F4 wing-body configuration (Fig 1). This geometry is representative of a modern transonic transport aircraft, and so is of interest to industry. Additionally, wind tunnel data from three different test facilities was publicly available for this geometry [12]. These two facts made it a logical choice as the subject geometry for DPW 1.

A composite drag polar from DPW 1 [2] is shown in Fig. 2. The polar is for a fixed Mach number of 0.75 and a Reynolds number of $3x10^6$. Experimental data is plotted using open circle symbols along with various colored lines representing the different CFD predictions. As mentioned in the introduction, the results are disappointing. The CFD predicted drag is generally higher than the experimental derived values and varies greatly among the various solutions. At a fixed-lift coefficient of 0.5, there is a 270 drag count spread in the CFD data. If the CFD "outliers" are not considered, then this spread improves to 40 drag counts; however, this is far worse than the approximate 10 count spread of the experimental data.

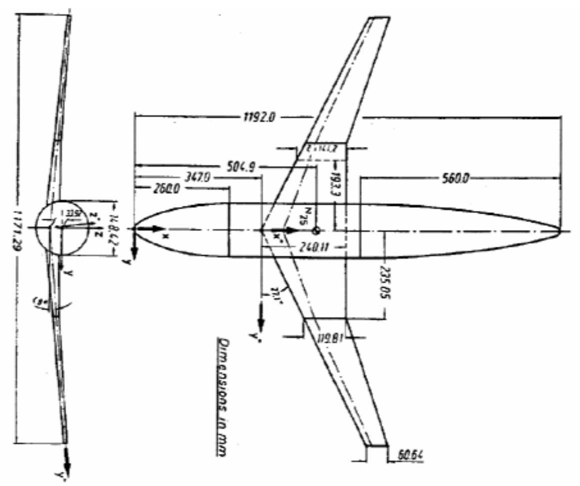

Fig. 1. DLR-F4 wing-body geometry.

Several of the participants presented full papers of their results at a special session of the 40th AIAA Aerospace Sciences Meeting and Exhibit held at Reno, Nevada in 2002 [1], [2], [13-16]. Included in this session are the DPW 1 data summary paper [2] and statistical analysis paper [1], which were subsequently published in the *AIAA Journal of Aircraft* [4] and [3].

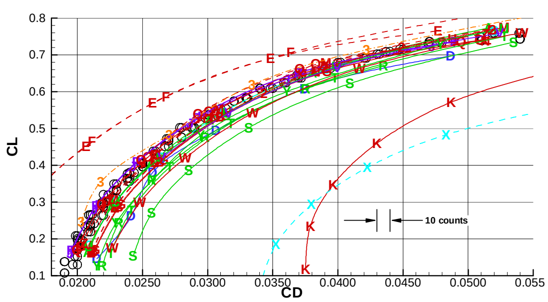

Fig. 2. DLR-F4 drag polar results from DPW 1.

At the conclusion of DPW 1, attendees discussed the results of the workshop and provided input for the planning of DPW 2. It was suggested that the large scatter in the results was primarily due to the inability of RANS codes to accurately model a separated flow region that occurred on the upper surface of the wing near the wing-body juncture at the trailing edge. Furthermore, it was suggested that the over prediction of drag was due to the fact that the CFD computations were performed as fully turbulent, whereas the boundary layer on the wind tunnel model had a run of laminar flow. Additionally, the provided multi-blocked structured grid had some grid quality issues that were not discovered prior to release of the grids to the workshop participants. These quality issues may also have contributed to the larger than expected scatter in the data.

In addition to the above comments, it was pointed out that it was generally accepted that CFD is able to compute delta drag levels between similar configurations very well and that this was how CFD was generally used in industry for the design and development of aircraft. Very seldom was CFD relied upon to provide absolute drag values. Additionally, many participants wanted to see more complex geometries considered.

2.3 DPW 2

The DPW organizing committee considered all of the above inputs when it chose the subject geometry and test cases for DPW 2. After much consideration and debate, the committee settled on the DLR-F6 geometry (Fig. 3).

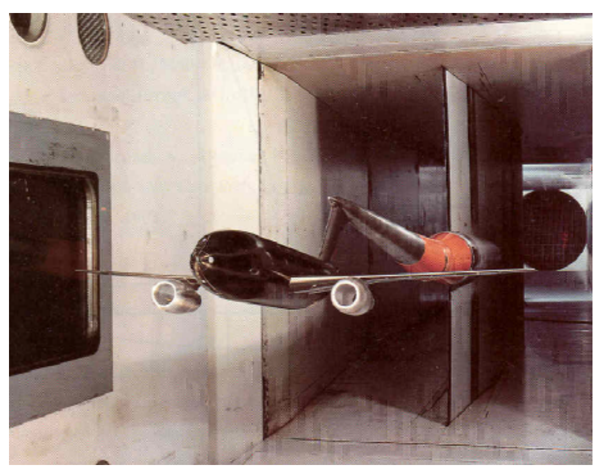

Fig. 3. DLR-F6 modle in ONERA S2MA wind tunnel.

Like the DLR-F4, the F6 is representative of a modern transonic transport aircraft. However, in addition to publicly available wing-body geometry and test data, wing-body-pylon-nacelle geometry and test data (Fig. 4) is also available [17].

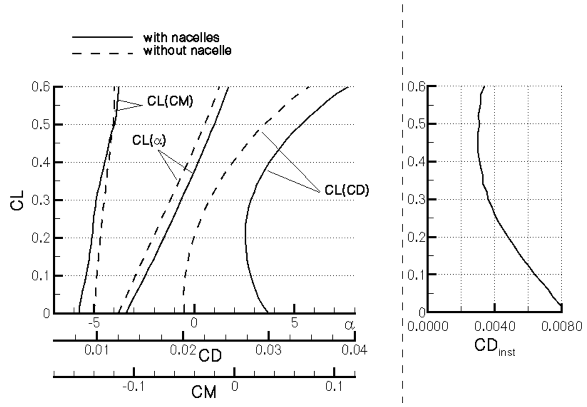

Fig. 4. DLR-F6 experimental data, Mach 0.75.

For DPW 2, participants were asked to perform both wing-body and wing-body-pylon-nacelle computations using both fully-turbulent and fixed transition boundary layer modeling techniques. An examination of delta drag predictions was conducted by considering both differences in configuration and differences in boundary layer treatment. In addition, a grid convergence study was attempted by asking participants to perform single point fixed-lift computations on a series of refined grids for both the wing-body and wing-body-pylon-nacelle configurations. There was a significant increase in the effort needed to perform required and optional test cases for DPW 2 as compared to DPW 1. Based on information collected from DPW 2 participants, it was estimated that more than 1.25 years of single computer processor time was collectively used by participants in performing the necessary computations for the workshop!

Despite the markedly increased demand on the participants' time and effort, DPW 2 saw an increase in both attendance and participation over the first workshop. DPW 2 was held in Orlando, Florida in June 2003 in conjunction with the 21st AIAA Applied Aerodynamics conference. Approximately 75 persons from five continents representing academia, research laboratories and industry attended the workshop. Twenty-five of those attending participated in the workshop, submitting data and presenting results.

Once again, flow separation was found to occur in the solutions and was suspected of increasing the scatter in the CFD predictions. Separation occurred on the upper surface of the wing at the inboard trailing edge. Separation also occurred along the entire span of the upper wing surface at the trailing edge. An additional area of separation occurred on the wing lower surface when the pylon and nacelle installation was considered (Fig. 5).

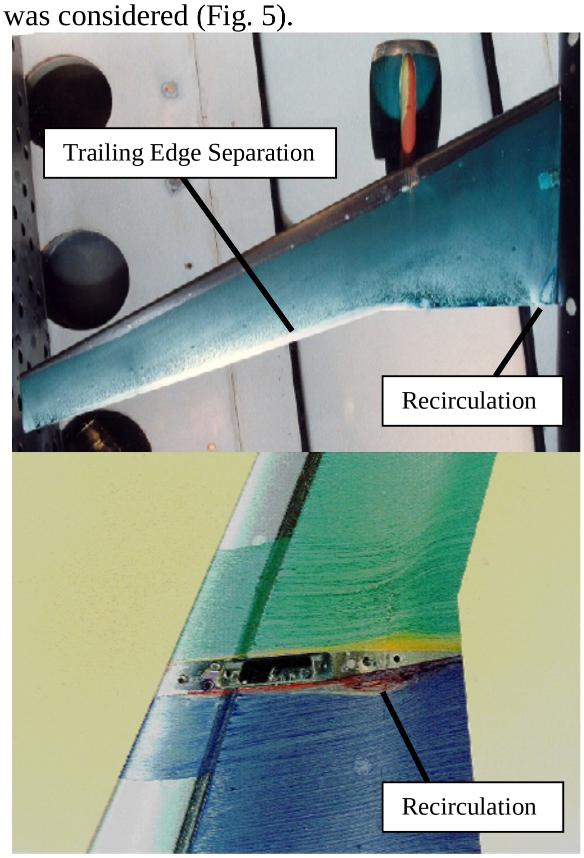

Fig. 5. DLR-F6 wind tunnel model with oil flow patterns.

In an attempt to quantify how the different CFD methods predicted the wing inboard separation, geometric data associated with various physical aspects of the separation (Fig. 6) was collected from the participants. The results showed that the separation shape and size varied wildly among the different solutions, illustrating the difficulty that RANS solvers have with separated flow.

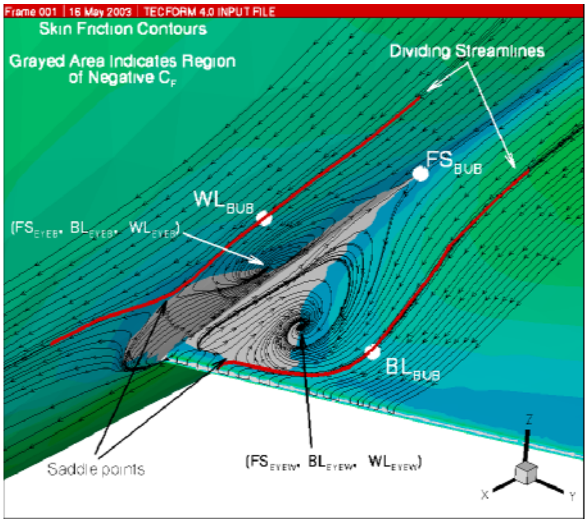

Fig. 6. RANS code predicted DLR-F6 inboard wing separation bubble, definition of measurement points.

Drag polar results of the DLR-F6 [5] are shown in Figs. 7-10. In each plot, CFD solutions (colored lines) are compared to experimental data (open circle symbols). These results are for a Mach number of 0.75 and Reynolds number of $3x10^6$. A grid convergence study was part of DPW 2, and in this series of plots, red curves correspond to CFD solutions obtained on course grids, blue on medium grids, and green on the fine grids.

The composite lift curve (lift coefficient versus angle of incidence (Alpha)) for the DLR-F6 wing-body configuration is shown in Fig. 7. The CFD results consistently over-predict lift at a given angle of incidence. This behavior was also true of DPW 1 results. Lift curve slopes are well predicted.

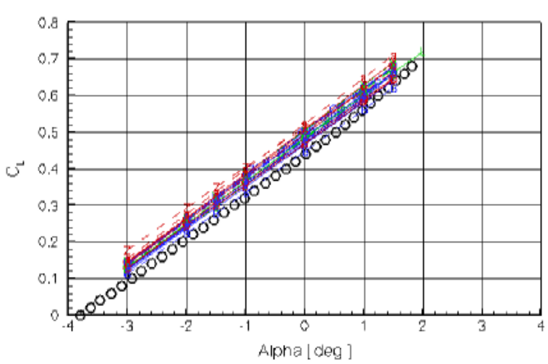

Fig. 7. DLR-F6 wing-body lift curve results from DPW 2.

Composite pitching moment coefficient curves for the DLR-F6 wing-body configuration are shown in Fig. 8. The majority of the computed data sets over-predict the nose-down pitching moment (more negative), as compared to the experiment. DPW 1 results also displayed a general over-prediction of nose-down pitching moment.

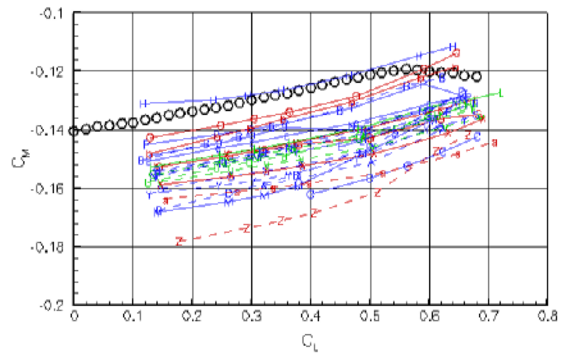

Fig. 8. DLR-F6 wing-body pitching moment results from DPW 2.

Fig. 9 and Fig. 10 show the composite idealized drag polars for the DLR-F6 wing-body and wing-body-pylon-nacelle configurations, respectively. The idealized drag coefficient,

$$C_D - C_L^2 / (\pi \ x \ (aspect\ ratio)),$$

is used instead of the total drag coefficient because it generally results in a more compact presentation of the data, allowing expanded scales. This, in turn, allows differences between data sets to be more discernable.

The CFD predictions generally under-predict drag for the wing-body configuration. The wing-body-pylon-nacelle drag is over-predicted for lower C_L values and slightly under predicted at higher values. The crossover point is near the DLR-F6 design cruise condition of C_L=0.5.

The range in C_D is about 35 drag counts for the wing-body configuration. This range is fairly consistent over the C_L values examined. The wing-body-pylon-nacelle configuration C_D range is about 55 drag counts for C_L values lower than 0.4. Above this point the range becomes larger, presumably due to larger variations in predicted separation regions as wing loading is increased.

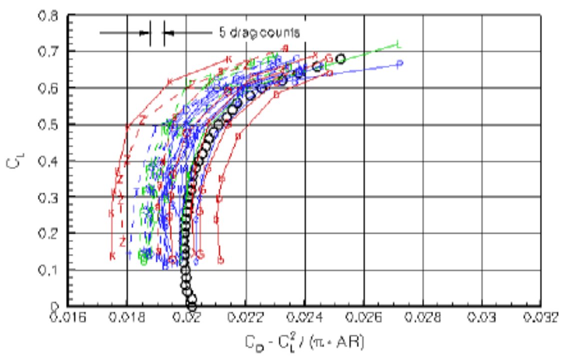

Fig. 9. DLR-F6 wing-body drag polar results from DPW 2.

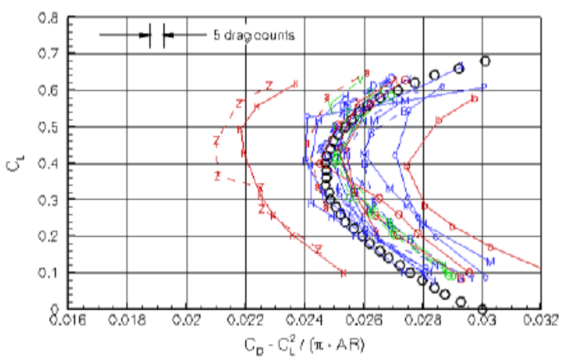

Fig. 10. DLR-F6 wing-body-pylon-nacelle drag polar results from DPW 2.

It is noted that the range in the CFD predictions decrease with increased grid density, but an improvement with grid resolution is not substantiated by the statistical analysis. Furthermore, the various series of course, medium and fine grids used are of insufficient density to obtain asymptotic solution convergence.

Even with the existence of separation, the DPW 2 results show a 3:1 (or better) reduction in the spread of the results, as compared to the DPW 1 results. However, the reduction in the dispersion of the core solutions is more modest; most of the improvement came about from better predictions of the "outlying" data sets. Incremental or delta drag values (not shown) tended to be considerably better in both scatter and median.

Invited papers from DPW 2 participants were presented at two special sessions at the 42nd AIAA Aerospace Sciences Meeting and Exhibit held at Reno, Nevada in 2004 [5], [6], [18-29]. Included in these sessions are the DPW 2 data summary paper [5] and statistical analysis paper [6]. The data summary paper was subsequently published in the *AIAA Journal of Aircraft* [7].

2.4 DPW 3

In an attempt to eliminate the issue of flow separation from DPW 3, the DPW organizing committee designed a wing-body fairing for the DLR-F6 that eliminated the pocket of flow separation occurring on the inboard portion of the wing upper surface. Fig. 11 shows RANS computed streamlines in this region for the original DLR-F6 geometry. Fig. 12 shows that the separation region has been eliminated with the addition of the wing-body fairing, which is given the designation FX2.

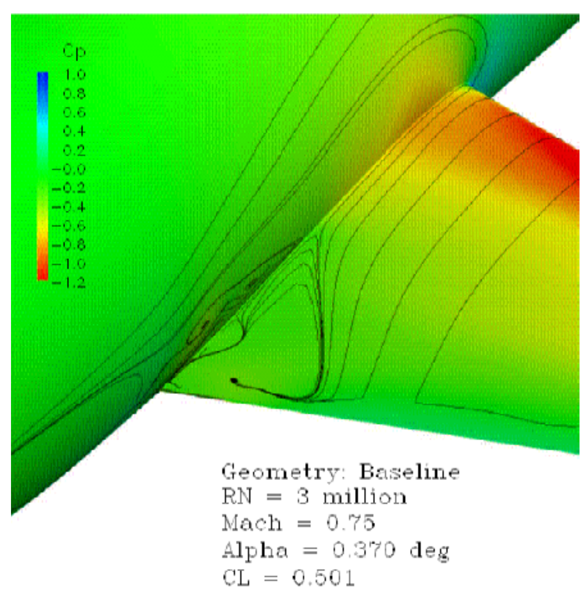

Fig. 11. RANS computed streamlines of DLR-F6 showing flow separation region.

In addition to the DLR-F6 and DLR-F6-FX2 geometry, two wing-along configurations were created by the DPW committee and designated DPW-W1 (Fig. 13) and DPW-W2 (Fig. 14). Both geometries are modern, transonic wings, with DPW-W2 derived from

DPW-W1 by performing a single-point design optimization. The two wings were added to provide "simpler" geometries in an attempt to encourage more academic participation in the workshops. The two wings also provide a means of computing delta drags on similar geometries, such as is routinely performed in aircraft development programs. Finally, because the wing-along geometries are simple, grid convergence studies can be more readily performed on them.

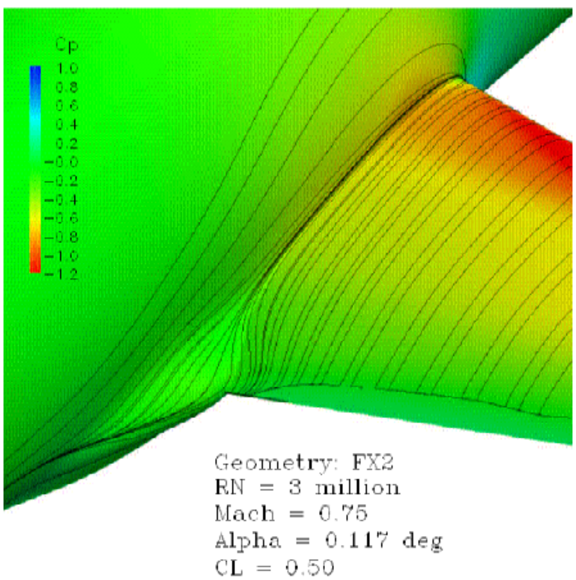

Fig. 12. RANS computed streamlines of DLR-F6 with FX2 fairing showing elimination of the flow separation region.

Neither DLR-F6-FX2 nor DPW-W1 and DPW-W2 have been tested in a wind tunnel. Therefore, DPW 3, for the first time in the DPW series, was a 'blind' CFD study. That is, participants did not have wind tunnel data to compare their solutions to as they were computing them. The scatter in a 'blind' study is potentially worse, as participants may not be aware of errors in their results due to, for example, incorrect solver input parameters that would otherwise be uncovered if wind tunnel data is available for comparison.

DPW 3 participants could choose to perform test cases on either the wing-body configurations (DLR-F6 and DLR-F6-FX2) or on the wing-alone configurations (DPW-W1 and DPW-W2). Both choices involved a grid convergence study.

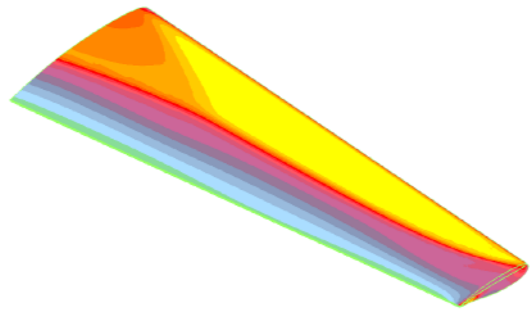

Fig. 13. RANS computed pressure contours of DPW-W1 at Mach 0.76.

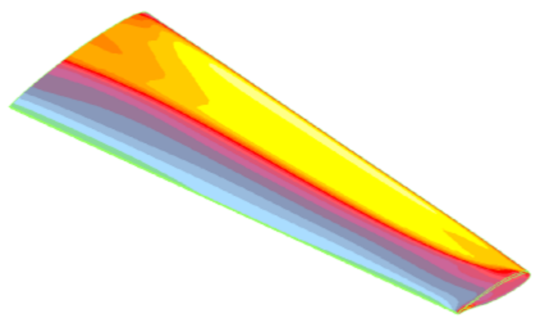

Fig. 14. RANS computed pressure contours of DPW-W2 at Mach 0.76.

A special session was held at the 23rd AIAA Applied Aerodynamics conference at Toronto, Canada in 2005 to publicly 'preview' the DPW 3 geometry and include results of on-going DPW related studies [30-33] and to inform the CFD and applied aerodynamics community of DPW activities.

DPW 3 was held in San Francisco, California in June 2006. About sixty-five persons were in attendance for the two day workshop. Final analysis of the DPW 3 data is still ongoing. Results for the DLR-F6 and DLR-F6-FX2 were not available at the time of this paper's submittal deadline. However, initial drag polar results for the DPW-W1 and DPW-W2 wings are given in Fig. 15 and Fig. 16, respectively. The drag range for these wing-alone geometries is about 10 counts. More scatter occurs in the DPW-W2 drag data at the optimized condition where the wing was shaped to produce an isentropic compression for reduced drag.

The data summary paper and statistical analysis paper for DPW 3 will be presented along with other DPW 3 invited papers at the 45th AIAA Aerospace Sciences Meeting to be held in Reno, Nevada in January, 2007. Workshop presentations, which include data summary and statistical analysis overviews, should be viewable prior to this meeting on the DPW website [8].

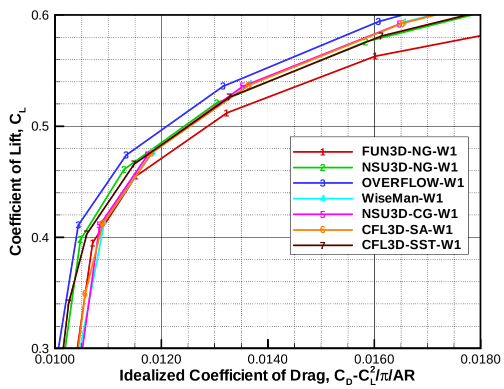

Fig. 15. DPW-W1 drag polar results from DPW 3.

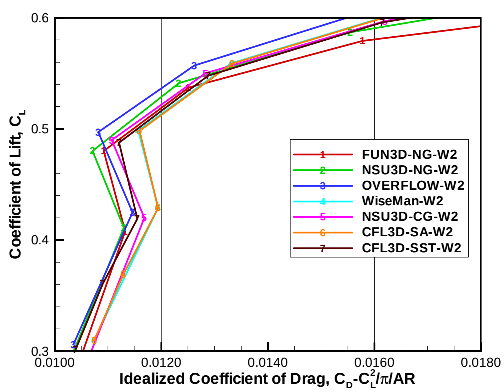

Fig. 16. DPW-W2 drag polar results from DPW 3.

4 Future Workshops

The DPW organizing committee is in the process of building hardware in support of testing the DLR-F6-FX2 geometry at both the ONERA S2MA and NASA NTF wind tunnel facilities. If these tests are carried out as planned, future workshops will likely focus on the DLR-F6-FX2, using the high quality wind tunnel data for comparison.

5 Closing Remarks

The DPW series has assessed state-of-the-art CFD methods for force and moment predictions, brought CFD users and developers together, and compiled a large and valuable collection of data and reference material that is assessable to the public. DPW has demonstrated that current CFD methods are deficient in regards to force and moment predictions; DPW 1 showed this, and five years later no appreciable advancements in physical modeling techniques, algorithms, or processes have been proposed to reduce the unacceptable scatter among the RANS predictions. Hopefully, by the time of DPW 4, improvements will have been implemented that reduce the scatter.

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