HIGH-LIFT PREDICTION WORKSHOPS: RETROSPECTIVE, LESSONS LEARNED, AND FUTURE PROSPECTS

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Abstract

A series of workshops focused on high lift, ongoing since 2010, is discussed. The series goal is to improve computational fluid dynamics prediction of flowfields near maximum lift, which has historically been very unreliable. The workshops center on CFD verification and validation exercises addressed in common by experts from organizations around the world, thereby enabling more rapid learning and improvement than would be possible with independent research alone. The workshop goals and structure are described, lessons learned to date are summarized, and potential future prospects for high-lift prediction are given.

Keywords: high lift, workshop, verification, validation

1. Introduction

The American Institute of Aeronautics and Astronautics (AIAA) Computational Fluid Dynamics (CFD) High-Lift Prediction Workshop (HLPW) series has been a highly successful, ongoing collaborative activity since 2010. The series brings together aeronautical engineers and other interested participants with the common goal of assessing and improving CFD's capability to predict the maximum lift ($C_{L,max}$) characteristics of modern transport aircraft. The main idea behind workshops of this type is that having a large group of people work on the same problem or test case will tend to advance the state-of-the-art more rapidly than if everyone was working independently on different problems. Therefore, these workshops are structured to provide the test cases that all participants compute in common with their CFD codes. By meeting together to compare the CFD results (typically against experimental data), the participants learn collectively what CFD strategies and models work best and what do not. As of the date of this writing, four HLPWs have been held, with a fifth scheduled to occur in early August 2024.

Summaries of the previous four HLPWs are provided in articles by Rumsey et al. [1, 2, 3, 4]. Other papers summarize specific aspects of the more recent workshops [5, 6, 7, 8, 9, 10, 11]. There have also been many dozens of papers covering specific CFD results by workshop participants, written primarily for special sessions at AIAA conferences. These are not cited here, but many are referenced in the four HLPW summary articles.

This article provides a look back at the series of HLPWs to date, with the objective of providing a broad overview of many of the lessons learned. Also, some thoughts on what the future may hold in the area of high-lift CFD prediction are offered.

2. General Organization and Conduct of the HLPWs

The stated goals of the HLPWs are to: (1) Assess the numerical prediction capability (meshing, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology/codes for swept, medium-to-high-aspect ratio wings for landing/take-off (high-lift) configurations, (2) Develop practical modeling guidelines for CFD prediction of high-lift flow fields, (3) Determine the elements of high-lift flow physics that are critical for modeling to enable the development of more accurate prediction methods and tools, and (4) Enhance CFD prediction capability for practical high-lift aerodynamic design and optimization.

The workshops, which are organized and run by a steering committee, always make use of high-lift configurations for which the geometry and measured data have unrestricted public availability, forming the basis for international cooperation and collaboration. Participation by anyone, regardless of their home organization or experience level, has always been encouraged. Other details about the HLPWs can be found on the workshop's website [12] and links contained therein.

The first and second workshops, held in 2010 and 2013, respectively, were independent events that focused on comparisons of mostly Reynolds-averaged Navier-Stokes (RANS) CFD results with wind tunnel data. The third workshop in 2017 continued along the same vein, but was unique in that it also partnered with a companion event: the First Geometry and Mesh Generation Workshop (GMGW-1). This partnership was formed because of the large influence that meshing is known to have on CFD solutions. The workshop consisted of both: (1) independent sessions for discussing CFD results and for discussing geometry/meshing challenges, and (2) co-located joint sessions with everyone together. This partnership was considered to be very successful, so it was continued for the fourth workshop in 2022.

The fourth workshop was also unique in a different way: it introduced the Technology Focus Group (TFG) workshop approach. In previous workshops, participants computed test cases independently, then submitted their results to the organizers, who collated and presented comparisons at the workshop. The participants had to wait until the workshop to see how their CFD results compared with others. In the new TFG approach, several working groups were formed well in advance of the workshop. These groups were centered around different types of technology: Fixed Grid RANS, Mesh Adaptation, High Order Discretization, Hybrid RANS/Large-Eddy Simulation (HRLES), and Wall-Modeled LES (WMLES). Each of these groups met regularly at virtual meetings during the year prior to the workshop, having discussions and sharing ideas and preliminary results. Then, at the workshop itself, each TFG leader presented summaries of their own group's results and lessons learned.

This new TFG workshop approach took advantage of the increased availability of Covid-era virtual meeting tools. In addition to including active participants, the virtual meetings could also easily include "observers," who could listen in and learn along with everyone else. Although it no doubt consumed more of the participants' time during the year before the workshop, the new TFG approach created opportunities for collective learning to take place well in advance of the workshop itself. Now, if one participant had an idea or insight, others could benefit immediately and adapt the idea to their own high-lift work. In addition, this approach allows participants to catch mistakes and coding bugs early, thereby potentially improving the overall quality of submitted CFD results at the workshop.

The TFG approach also brought a new focus to the rapidly developing scale-resolving simulation methodologies of HRLES and WMLES, which use LES in certain regions of the flow. Prior to HLPW-4, almost all submitted solutions were RANS, and, as will be described later in the article, RANS appears to be unable to predict the characteristics of $C_{L,max}$ accurately and consistently. It is currently believed that HRLES and WMLES offer more potential for accurately predicting high-lift flows near stall. The fifth workshop in 2024 continued to use the TFG approach, with the same group divisions.

It is important to note that starting with the third workshop, the high-lift Common Research Model (CRM-HL) [13, 14] made its first appearance. Specifically developed for the purpose of CFD validation in an open, collaborative environment, this configuration includes many of the characteristics of modern high-lift transport aircraft. It plays a central role in a broad ecosystem of high-lift testing and CFD validation [15] that is already underway worldwide. It is expected that wind tunnel tests of the CRM-HL will explore different Reynolds number regimes, will focus on a variety of flow physics measurements, will involve both semispan and fullspan test articles, and will include diverse aspects such as icing, landing gear, and other configuration enhancements. Because of the wide array of ecosystem measurements expected, the CRM-HL will continue to be the focal configuration of HLPWs in the foreseeable future.

3. Lessons Learned from the HLPWs

The following subsections describe each of the HLPWs and summarizes their findings.

3.1 HLPW-1

The first workshop in 2010 focused on the NASA trapezoidal wing test article, a simplified semispan body and swept wing that included a slat and flap. Although parts of the experimental data from two different wind tunnels have been used in previous studies [16, 17, 18, 19, 20, 21], collectively the data have never been officially published. This workshop focused on the data taken in the NASA Langley 14- by 22-Foot Subsonic Wind Tunnel, with Reynolds number based on mean aerodynamic chord (MAC) of $Re_{MAC} = 4.3$ million.

There were 21 workshop participants who submitted 39 data sets of CFD results. At that time, CFD capability was far more limited than it is today, and most of the workshop grids did not include the flap fairings or slat brackets (which we now know can have big influence, especially near $C_{L,max}$). The finest grid sizes for HLPW-1 were on the order of 50 to 200 million nodes or cells, with typical "best practice" grids well less than 100 million nodes or cells.

CFD results collectively tended to underpredict lift, drag, and the magnitude of the pitching moment (moment was negative, or nose down) compared to experiment. In general, trends with grid refinement were generally in the correct direction (approaching the experimental data). For example, the lift coefficient for most entries increased as the grid was refined. Predicting the flow was more difficult at higher angles of attack nearing stall; there was more spread among the CFD solutions there, and some participants predicted early stall. See Figure 1, which is made up of mostly RANS results, including at least five different turbulence models.

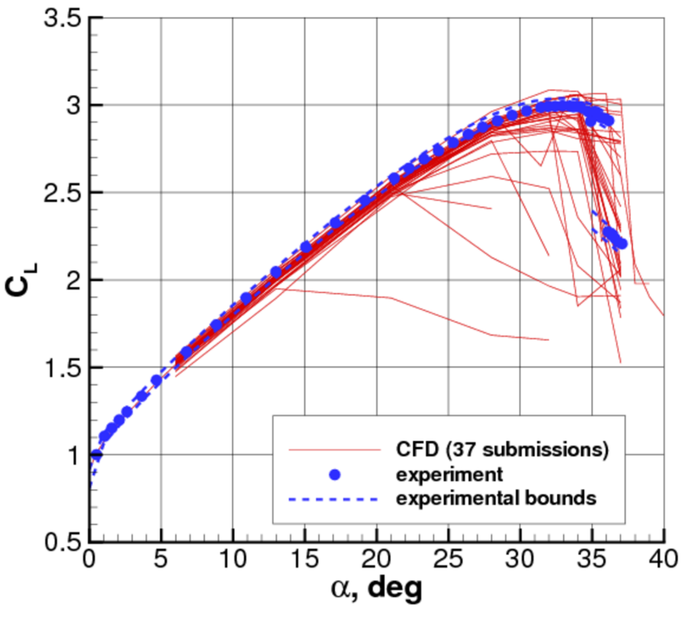


Figure 1 – HLPW-1 lift curve results (NASA Trapezoidal Wing test article), $Re_{MAC} = 4.3$ million.

One of the learnings from HLPW-1 that has carried over through all the subsequent workshops is the potential for CFD solutions at high angles of attack to be dependent on initial conditions. Starting from freestream conditions, a computation near stall sometimes yielded a solution with excessive separated flow (so-called “low-lift branch"), that the flow solver could not recover from. Participants found that by starting from a converged solution at a lower angle of attack, this overly-separated solution could sometimes be avoided. A related discussion of CFD multiple solutions for high-lift flows can be found in Kamenetskiy et al.[22]

Most participants used the Spalart-Allmaras (SA) turbulence model [23]. Other RANS turbulence models, including the k-ω shear stress transport (SST) model [24], had a greater tendency to separate and yield lower lift levels at high angles of attack. Because the untripped experiment was conducted at a Reynolds number significantly lower than flight Reynolds numbers, transition may have had some influence. However, most CFD was conducted fully turbulent. A few participants who employed transition modeling achieved higher lift levels than other models near stall. Some other general conclusions from HLPW-1 were as follows. The flowfield near the wing tip was more difficult to predict accurately than the inboard wing. Tetrahedral grids were found to exhibit greater grid sensitivity than the same grid with its boundary-layer tetrahedra merged into prisms. And finally, the deltas due to a configuration change (flap deflected 20° instead of 25°) were significantly overpredicted (collectively) by the CFD, but only with the NASA trapezoidal wing at a high angle of attack approaching $C_{L,max}$.

3.2 HLPW-2

The second workshop in 2013 focused on the DLR-F11 test article in landing configuration [25, 26]. This test article was tested at two different Reynolds numbers ($Re_{MAC} = 1.35$ million and 15.1 million), so a major goal was to learn how well CFD could predict the Reynolds number effect.

There were 26 workshop participants who submitted 48 data sets of CFD results. The test cases included a grid convergence study (on the configuration without fairings or brackets), a Reynolds number study on a close approximation to the full configuration (including fairings and brackets), and an optional full configuration study (including fairings, brackets, and bracket pressure tube bundles). The finest grid sizes for HLPW-2 were typically only somewhat finer than those used in HLPW-1, with most “best practice" grids still well less than 100 million nodes or cells.

This was the first HLPW for which a turbulence model verification case was included: the 2-D bump from the NASA Turbulence Modeling Resource (TMR) website [27]. The purpose was to identify potential inconsistencies in turbulence-model implementations. Here, among several participants who performed the exercise using the SA model, there was near-perfect consistency among three entries, one other entry was very close, and two exhibited notable differences and therefore likely had coding errors or a nonstandard version of the model implemented.

This was also the first HLPW at which it was noted (based on oil flow images) that near stall the slat brackets were influential in causing wedge-shaped regions of separated flow near the rear portion of the main wing. This characteristic confirmed that the inclusion of all bracket hardware is required to have any chance to capture the physics of the separated flow regions when running CFD on high-lift configurations near $C_{L,max}$. In fact, most entries without brackets tended to predict increasing lift well past the nominal stall angle. Although only a few participants computed on the full configuration, their results suggested that the pressure tube bundles that lay alongside the slat brackets had some influence on the flowfield near stall. For all configurations the pressure coefficients and velocity profiles indicated that differences between the CFD results tended to be larger on the flap as well as at the outboard stations of the wing.

Similar to HLPW-1, most of the CFD results used RANS with SA-based turbulence models, but a few other models and methods were also tried. Again, the CFD results as a whole exhibited greater scatter near $C_{L,max}$ than in the linear regime of the lift curve. However, for this workshop, there were no clear trends with turbulence or transition modeling. The Reynolds number trends were only qualitatively captured by the collective CFD results, shown in Figure 2. At the lower Reynolds number of 1.35 million, the CFD predicted a surprisingly wide band of results even in the linear portion of the lift curve. From the grid convergence study, it was difficult to discern how much refinement was needed because the CFD scatter in results did not decrease beyond a certain grid-refinement level. Some of this non-negligible scatter may have been due to difficulties that many participants encountered trying to iteratively converge the cases.

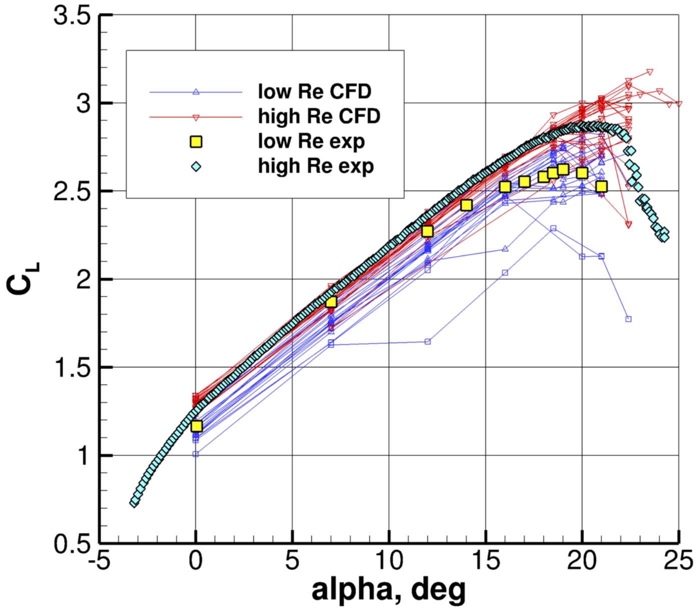
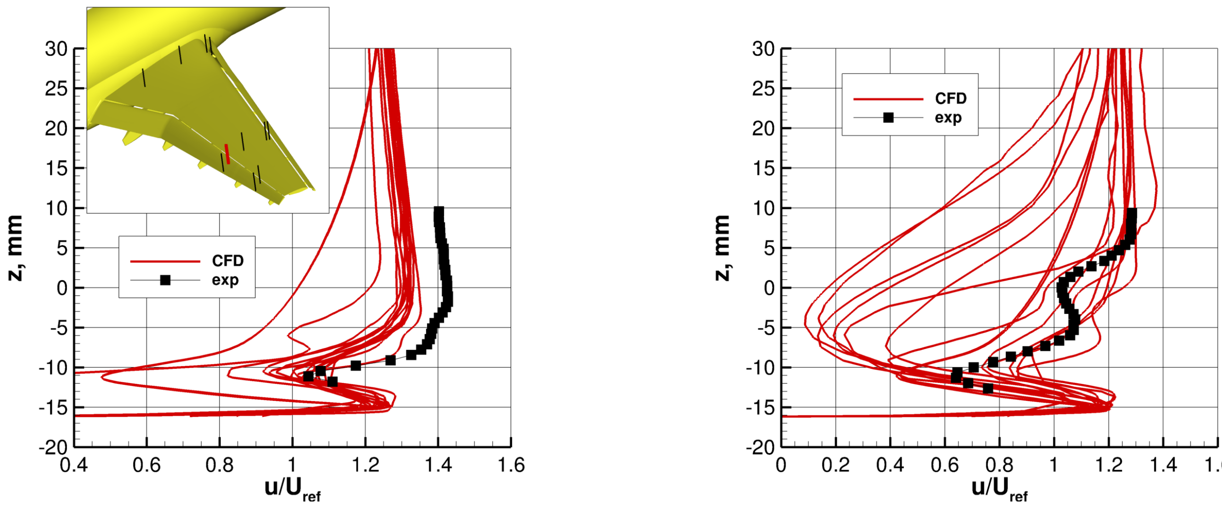


Figure 2 – HLPW-2 lift curve results (DLR-F11 test article), $Re_{MAC} = 1.35$ and 15.1 million.

The HLPW-2 experimental data included velocity profiles obtained using Particle Image Velocimetry (PIV). These can be challenging measurements in some wind tunnels; there has been no velocity data published for any of the other HLPW configurations since this DLR-F11 test. The CFD comparisons with this data were generally quite poor (for unknown reasons). Furthermore, at maximum lift conditions the CFD exhibited a very wide spread of results, exhibiting lack of consistency. Example velocity comparisons for $Re_{MAC} = 1.35$ million are shown in Figure 3. The location of the profiles is given by the red line in the inset figure.



(a) $\alpha = 7^\circ$.

(b) $\alpha = 18.5^\circ$.

Figure 3 – HLPW-2 example velocity profiles on outboard flap for DLR-F11 at $Re_{MAC} = 1.35$ million.

3.3 HLPW-3

The third workshop in 2017 focused on a “clean" (without fairings or brackets) version of the CRM-HL configuration as well as on the full-configuration Japan Aerospace Exploration Agency Standard Model (JSM) [28, 29, 30, 31]. The former was a CFD-only study, while the latter was a nacelle/pylon installation study on a high-lift configuration that included all flap and slat support hardware, tested at $Re_{MAC} = 1.93$ million.

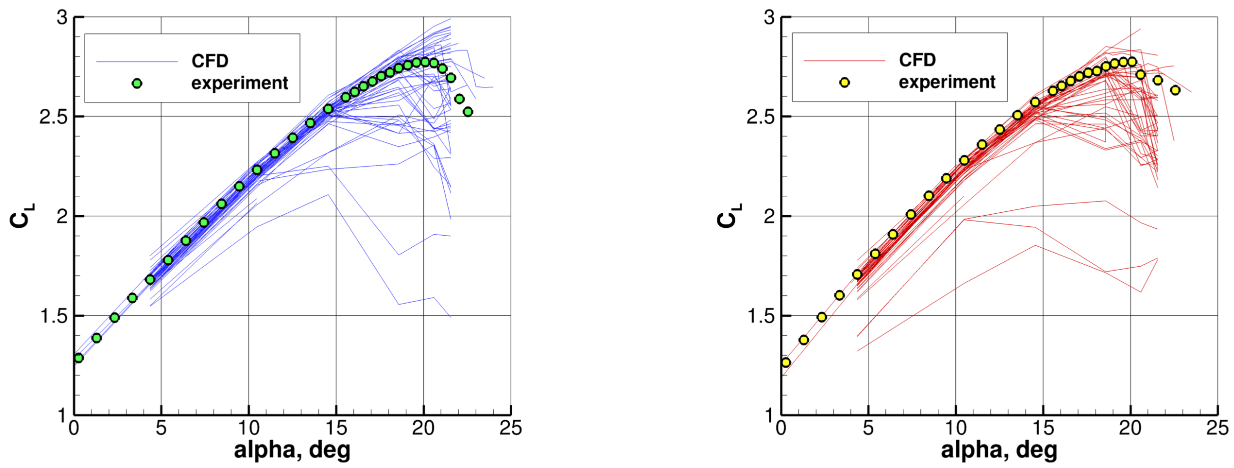
There were 35 workshop participants who submitted 79 data sets of CFD results. The CFD-only grid convergence study on the CRM-HL configuration also included an optional exploration of the effects of a partial seal between the two parts of the flap. The second test case on the JSM included comparisons with experimental data both with and without the nacelle/pylon installed. The finest committee grid sizes for HLPW-3 varied widely, between about 200 to 550 million nodes and 400 to 1200 million cells. The “best practice" (medium) grids for the full-configuration JSM ranged between about 20 to 230 million nodes and 65 to 230 million cells.

Like the previous high-lift workshop, HLPW-3 included a verification test case: a 2-D airfoil near-wake case from the NASA TMR website [27]. Like in HLPW-2, most participants performed the verification exercise using the SA model. Notably, only 6 out of 19 of the CFD codes (32%) appeared to be fully verified for SA (agreeing nearly perfectly with the two reference codes) based on two measures of the drag coefficient and minimum u-velocity at a specific x-location in the airfoil wake. The CRM-HL results using SA were then downselected to highlight only those codes that passed the SA verification test. Although not fully conclusive, the study noted that three verified codes used for the CRM-HL yielded more consistent results than the SA results as a whole. This suggests that some of the variation seen among CFD results at workshops may be due to codes that have not verified their turbulence model implementations. Presumably, with the implementation of the SA model verified, any remaining differences between results would only be a result of discretization errors and/or errors due to insufficient iterative convergence, both of which can be difficult to eliminate on a complex 3-D configuration. Also, the effect of different initial conditions possibly leading to diverse “high-lift" vs. “low-lift" branch solutions cannot be ignored.

In the CFD-only study on the CRM-HL configuration, the effect of the partial flap seal was predicted inconsistently, especially at lower angles of attack at which flap separation is more prevalent. Similar to HLPW-2, the grid convergence study revealed a spread between CFD code results that did not diminish between the medium and fine grid levels. Again, the largest differences in surface details and boundary-layer profiles tended to be over the flap as well as outboard. Overall, collective CFD results on the JSM were again similar to previous workshops, with tighter clustering of results in the linear lift-curve range and very large scatter in results near maximum lift. Other than near $C_{L,max}$, the deltas between nacelle/pylon on and off were fairly well predicted (see Figure 4).

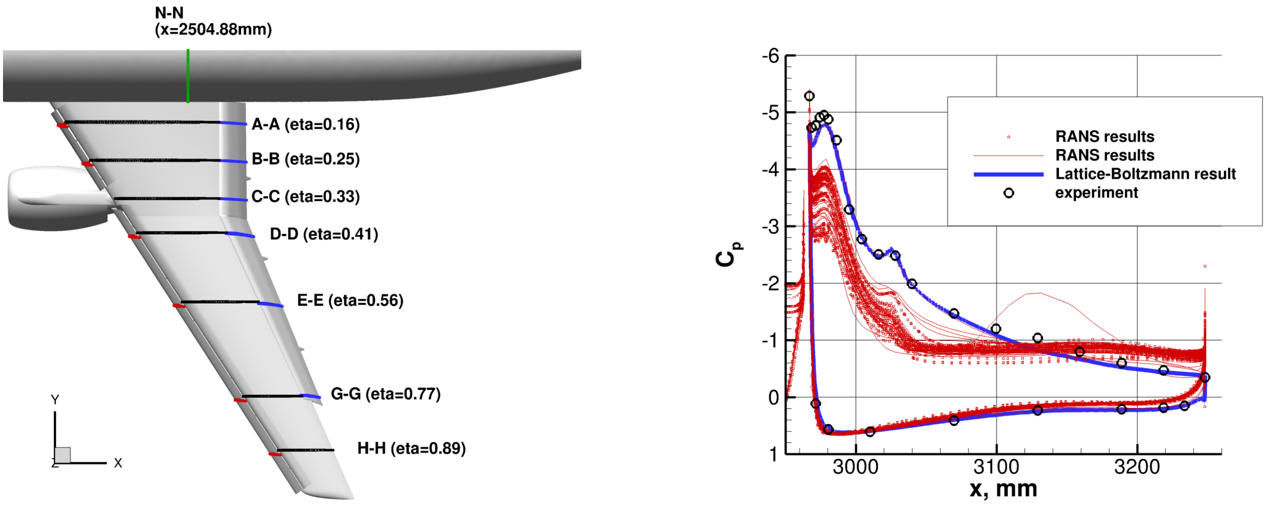
At the low Reynolds number of the JSM experiment, transition likely plays a significant role, but transition model results at the workshop were inconsistent near maximum lift. Also, some individual RANS results run fully turbulent yielded reasonable lift curve predictions. Further muddying the waters was the fact that adequate grid convergence was not clearly demonstrated near $C_{L,max}$, making it difficult to draw firm conclusions about CFD’s ability to predict the flow in that regime.

Nonetheless, a major conclusion from the workshop (from surface pressure evidence as well as from surface flow visualizations presented at the workshop) was that when RANS achieved reasonable results in terms of integrated lift near $C_{L,max}$, it was typically for the wrong reasons. In particular, RANS results tended to predict too much outboard separation on the main wing behind one or more of the slat brackets, while underpredicting the separation near the wing root. An example surface pressure coefficient (C_p) plot is shown in Figure 5, showing significant collective CFD-predicted separation (flat C_p levels) along an outboard station on the main wing, while experiment shows none. This behavior drew attention to the importance of collecting computed surface streamlines from participants, which



(a) No nacelle/pylon. (b) With nacelle/pylon.

Figure 4 – HLPW-3 lift curve results (JSM test article), $Re_{MAC} = 1.35$ million.



(a) Locations of C_p extraction. (b) Along H-H on main wing.

Figure 5 – HLPW-3 example C_p results for JSM (with nacelle/pylon) at $\alpha = 18.58°$.

was done at subsequent HLPWs. On the other hand, a scale-resolving lattice Boltzmann method appeared to demonstrate that it could better match the experimental separation patterns than the RANS results. In fact, this technique produced C_p results that closely matched the experimental data along H-H in Figure 5(b).

At HLPW-3, there was statistical evidence suggesting that over the four years since HLPW-2, participants had achieved more consistency predicting the flow over the JSM type of high-lift configuration (at low Reynolds number and with all bracket hardware), but only at angles of attack well below stall. Consistently accurate computations near maximum lift conditions (using RANS) remained collectively elusive.

3.4 HLPW-4

Beginning with the 2022 workshop, the CRM-HL configuration from ecosystem experiments became the primary focus. The particular test article used in HLPW-4 was the NASA 10% semispan configuration, tested in the QinetiQ wind tunnel [32]. CFD comparisons were made with experimental results acquired at $Re_{MAC} = 5.49$ million. As mentioned earlier, HLPW-4 introduced the use of TFGs and collaborative exploration in groups prior to the actual workshop. These TFGs developed "Key

Questions" that they attempted to answer during the course of their investigations [7, 8, 9, 10, 11]. Like HLPW-3, this workshop continued to partner with the GMGW group in order to highlight the importance and impact of meshing on CFD solutions.

There were 44 workshop participants who submitted 184 data sets of CFD results. The first test case was a flap deflection study at low angle of attack, exploring the effects of three different settings. The second test case focused on prediction of the flow near $C_{L,max}$, with the option of including the effects of tunnel walls. Nearly 170 different CRM-HL meshes were created and submitted in support of the workshop; some of these were created by the workshop committee, and some were created by participants. In general, the committee grids intended for RANS were roughly similar in size to those from HLPW-3. There has not been a summary made of all the non-committee grid sizes. However, typical non-committee submitted grids intended for scale-resolving simulations ranged from about 150 to 600 million nodes.

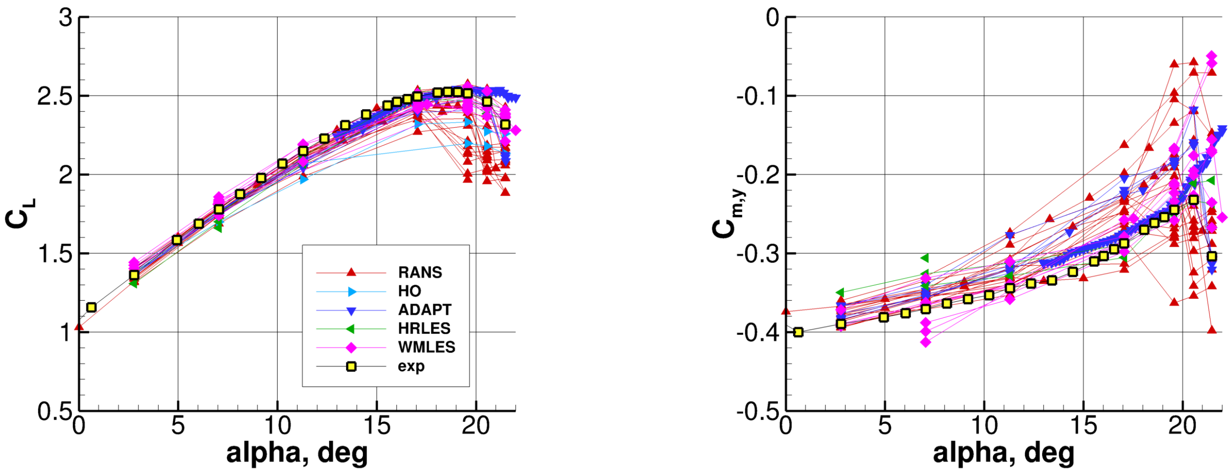
Turbulence model verification was again pursued in this workshop. This time, a 2-D multielement airfoil case from the NASA TMR website [27] was employed, and it was requested that participants only submit SA results. Overall, the exercise proved to be successful for most participants. Of those results submitted, a few minor issues were evident in some solutions, but all except two submissions produced solutions that appeared to be acceptably approaching the benchmark collective solution. This success rate represented a dramatic improvement from the HLPW-3 verification test. However, SA-verified codes that were run on the CRM-HL grid convergence study still showed a big spread with grid refinement. The reason for this is not known, but it was hypothesized that additional refinement of the meshes far beyond the current levels used in the fixed grids would be required to bring the solutions closer together.

Geometry preparation and fixed-grid meshing for high-lift flows was still acknowledged to be very difficult. It is not clear how to best handle complex regions like junctions and pinch points. It is also very difficult to determine fixed-grid guidelines (particularly spacing constraints) for different methodologies, codes, and regions of the lift curve. Many groups are limited to use of meshes with no more than a few hundred million unknowns, and so mesh influence is still quite dominant for high-lift problems. Mesh adaptation represents a possible solution to this issue, but most CFD codes still do not possess this capability.

A major conclusion from HLPW-4 was that RANS was unreliable for predicting the forces and pitching moment accurately and consistently near $C_{L,max}$. See the red delta, light blue right triangle, and dark blue gradient results in Figure 6. And, even for the few cases when lift was predicted reasonably well, it could be shown to be for the wrong reasons: RANS usually predicted much more outboard separation than the wind-tunnel test article near $C_{L,max}$ and too little inboard separation beyond stall. An example of excessive RANS outboard separation at $C_{L,max}$ is shown through a comparison of surface streamlines with oil flow in Figure 7. RANS also failed to correctly predict flap deflection effects at low angles of attack. Both of these situations involve flow separation, which appears to be a key flow feature that RANS is unable to predict accurately and consistently.

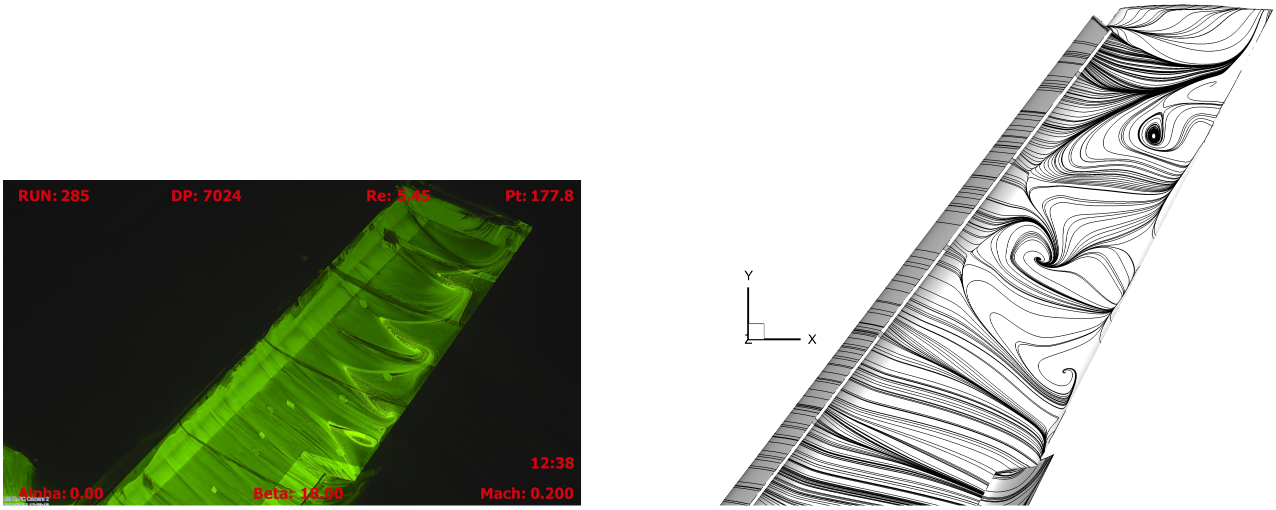
Both high-order numerics and mesh-adaptation technology were focal efforts in HLPW-4. The high-order results for the 2-D verification exercise were very encouraging, but the high-order CRM-HL results did not fare as well compared to other methods. Nonetheless, this is still considered an emerging technology, and much progress was made over the course of the TFG meetings for this workshop, particularly with respect to advancements in high-order meshing.

Mesh adaptation technology demonstrated its value in HLPW-4 by bringing much more consistency to the high-lift RANS results. Adapted results for the SA turbulence model were typically very close to each other in terms of surface flow topology, and there was some evidence that multiple solutions (particularly the low-lift branch) could be avoided by combining mesh refinement with machine-



(a) Lift coefficient. (b) Moment coefficient.

Figure 6 – HLPW-4 lift and moment curve results (NASA 10% CRM-HL test article), $Re_{MAC} = 5.49$ million.



(a) Oil flow. (b) Typical RANS surface streamlines.

Figure 7 – HLPW-4 surface flow visualization near $C_{L,max}$, $\alpha = 19.57°$.

precision-level iterative convergence. Mesh refinement was also shown to automatically track and better resolve the vortices and wakes in the CRM-HL flowfield.

Scale-resolving simulation methods (HRLES and WMLES) appeared to be most promising for predicting $C_{L,max}$. Generally, results using these techniques produced the most accurate forces and moment compared with experiment at maximum-lift conditions (see the green left triangle and pink diamond results in Figure 6. On the outboard part of the wing, they produced less separation than RANS (compare Figure 8 with Figure 7), in better agreement with the measured oil flow data. Inboard, near the wing root, there is still some question as to the influence of the tunnel floor boundary layer near $C_{L,max}$; so, it is not yet clear what the correct flow pattern should be there when running in free air.

There were still some notable inconsistencies among the scale resolving results, particularly in velocity profiles. And, at low angles of attack, the scale-resolving methods were collectively less accurate than RANS. Therefore, more work is needed to mature these approaches and establish best-practice

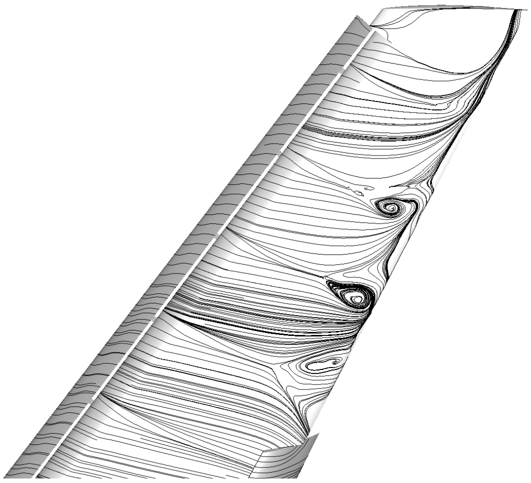
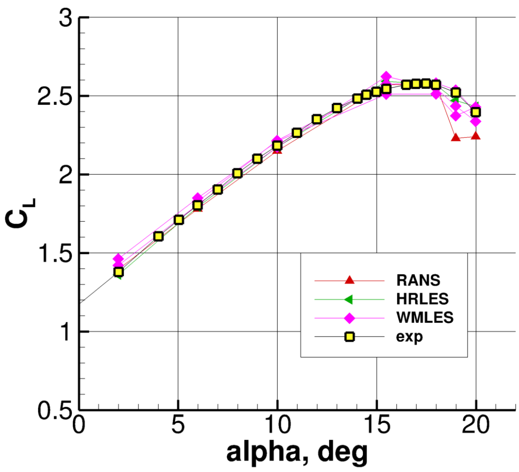
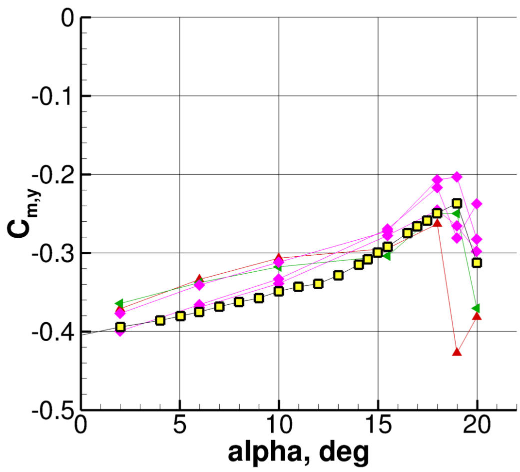


Figure 8 – HLPW-4 typical WMLES surface streamlines near $C_{L,max}$, $\alpha = 19.57^\circ$.



(a) Lift coefficient.



(b) Moment coefficient.

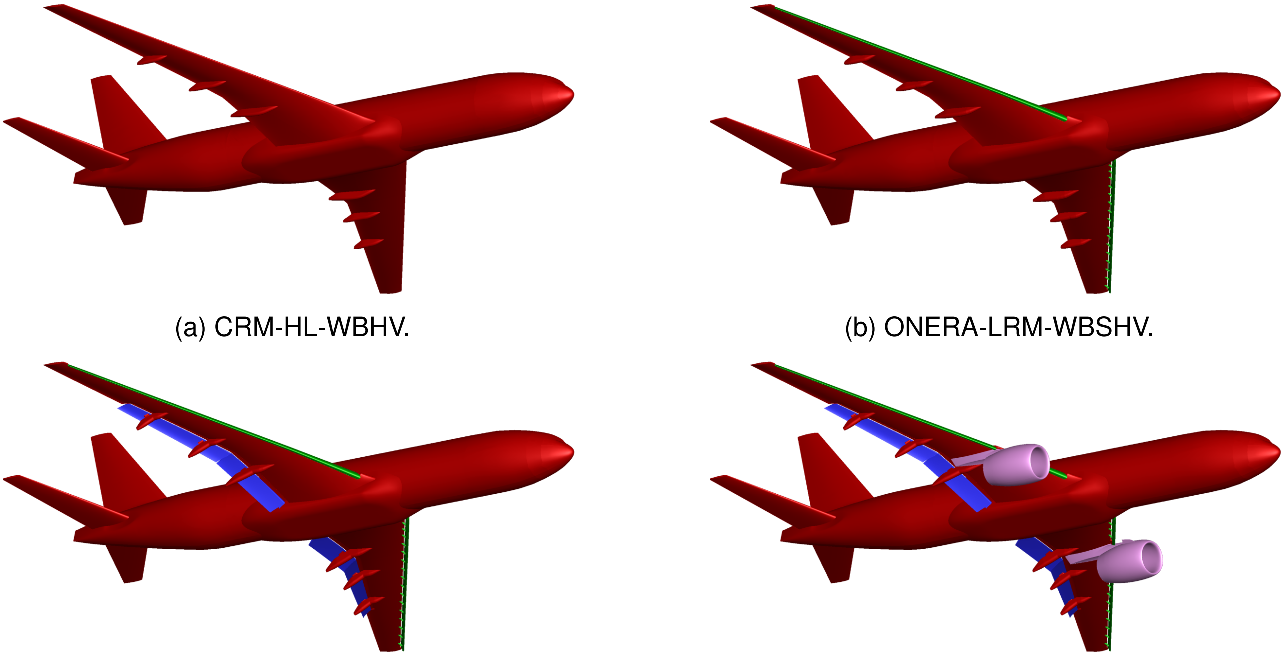
Figure 9 – HLPW-4 lift and moment curve results computed in QinetiQ tunnel (semispan NASA 10% CRM-HL test article).

guidelines.

It is worth noting that although there were only five entries that ran the CRM-HL in the QinetiQ wind tunnel, all results were excellent compared with the uncorrected experimental lift and fair compared with experimental moments (Figure 9). One entry used RANS, one used HRLES, two used WMLES, and one used lattice Boltzmann with a type of LES modeling. It is likely, however, that RANS was not capturing the correct separation physics; there was excessive wing separation behind the nacelle at $\alpha = 18.97^\circ$ and excessive separation both inboard and outboard at $\alpha = 19.98^\circ$. See details in the subsequent paper by Duensing et al.[33]

3.5 HLPW-5 to Date

As of the time of this writing, the TFGs for HLPW-5 have been meeting regularly for about a year. The same TFG categories from HLPW-4 are being used. The particular CRM-HL test article being compared against is the ONERA 5.1% full-span configuration (termed LRM-HL by ONERA) [34]. The test case is a configuration buildup, which includes the full landing configuration ONERA-LRM-LDG-HV (wing-body-slat-flap-nacelle along with empennage), ONERA-LRM-WBSFHV (wing-body-slat-flap along with empennage), and ONERA-LRM-WBSHV (wing-body-slat along with empennage). Another part of the buildup to be tested later by Boeing is a different version of the same configuration, the CRM-HL-WBHV (wing-body along with empennage). Each of these four configurations is illustrated in Figure 10. This sequence of four configurations challenges the CFD to predict differences due to the presence of various geometry components. Furthermore, it should help establish which components cause the CFD models the most trouble.



(a) CRM-HL-WBHV.

(b) ONERA-LRM-WBSHV.

(c) ONERA-LRM-WBSFHV.

(d) ONERA-LRM-LDG-HV.

Figure 10 – HLPW-5 configuration buildup geometries using the CRM-HL.

HLPW-5 also includes a Reynolds number study ($1.05 < Re_{MAC} < 30$ million). Here, the ecosystem test article is primarily the semispan NASA 5.2% CRM-HL configuration. However, it is currently not clear whether experimental data will be available in time for the workshop. If not, then the workshop's Reynolds number test case will be CFD-only, with a focus on establishing best practices for achieving grid-converged results, particularly at the highest (flight-scale) Reynolds numbers.

Finally, the workshop also includes a verification case, the CRM-HL-WB, which is simply the cruise wing-body configuration at a specific angle of attack below stall. It is felt that on today's supercomputers, sufficiently fine grids can be run for this case to achieve adequately grid-converged results using the SA turbulence model (for RANS). It is also hoped that enough participants can run using other models (such as SST) to help establish valid reference solutions that could be used for verification. The verification case is also of interest for the scale-resolving simulation methods, to see if a variety of different methodologies can achieve a similar result.

4. Overall Workshop Trends and the Future of High-Lift CFD Prediction

One of the main takeaways from the many years of the HLPWs has been the overall failure of RANS methods to accurately predict high-lift flowfields near stall. To be sure, there have always been some RANS submissions over the course of the workshops that have compared reasonably well with experimental measurements, particularly with regard to lift coefficient prediction. However, typically these reasonable-looking results have been shown to have incorrect flow physics (surface flow patterns) compared with experimental oil flow results near $C_{L,max}$. The overall failure of RANS has been attributed to its inability to accurately predict separated flows, especially when the separation coverage is significant.

There are other known areas where RANS often fails, but in many cases there have been fixes or models developed that can adequately address them. One example is juncture flow, where two surfaces (like the wing and body) meet to form a junction, and the flow runs along the corner. It is now well-known that Boussinesq eddy viscosity models cannot predict an important aspect of juncture flows: the anisotropy in the normal stresses, which can drive stress-induced vorticity deep in the corner and reduce the tendency to separate in an adverse pressure gradient. However, many nonlinear models are known or have been developed that can adequately correct this deficiency. An example is given in Rumsey et al.[35] Another area important for high lift is vortical flow. On a typical complex high-lift configuration, there are many regions where streamwise vorticity develops and passes downstream, often affecting the flow over the vehicle wing. CFD typically diffuses such vorticity too quickly compared to reality, both because of inadequate grid resolution and because RANS turbulence models often add eddy viscosity in vortex core regions, further exacerbating the problem. But turbulence models exist that do a better job in vortical flows, such as the RC model [36] and second-moment Reynolds stress models like that of Eisfeld et al.[37] Unfortunately, attempts to use improved models like these for HLPW configurations have typically yielded results no better than simpler models. This failure of the improved models is likely because they do not perform any better for separated flows, and separation issues tend to dominate.

Another important takeaway from the HLPWs has been the difficulty in getting CFD results to agree well with each other, even when they are ostensibly using the same modeling/methodology. Such agreement is crucial; otherwise, little is learned regarding the efficacy of a given model. Some of this situation has been improving because of HLPW's consistent focus on RANS verification testing, which has helped to raise awareness of the importance of verifying correct/consistent turbulence model implementations in CFD codes. Much has been done for SA-based models to date, but very little has been done for other models like the two-equation SST model. We have also learned that even when multiple codes have verified their implementation of SA, they can still exhibit inconsistent results for a complex high-lift configuration. Assuming that CFD solutions are not getting stuck near a “low-lift" branch solution, this inconsistency implies that the CFD grid is still too coarse to lie in the asymptotic range of grid convergence and/or the CFD codes have failed to achieve sufficient iterative convergence.

Many in the CFD community understand the importance of verification/consistency, and are pushing either mesh adaptation and/or high-order methods to help achieve it. These methods, which make up two of HLPW's TFGs, try to attain grid-converged and iteratively-converged CFD solutions at a reduced cost. The adaptation approach puts grid refinement where it is needed, and reduces or minimizes it elsewhere. The hope of high order is that it will robustly achieve a given level of numerical accuracy with far less cost than traditional second-order CFD methods. Both of these methodologies are currently focused primarily on RANS, but one group is already routinely performing high-order WMLES [38], and there appears to be growing interest to develop grid adaptation techniques for scale-resolving applications.

In spite of the problems with RANS, it still remains the workhorse CFD method for predicting aeronautical flowfields. RANS CFD codes today are generally entrenched within well-established organizational processes and are affordable and useful. And even when they do not predict high-lift flows accurately, they can occasionally provide some valuable insights to designers and analysts. Now, however, there is a trend toward development and incorporation of scale-resolving simulation tools into CFD toolboxes. Despite the higher cost of these newer CFD tools, the HLPWs have helped to demonstrate the ability of methods like HRLES and WMLES to more accurately predict flowfields near $C_{L,max}$ for the right reasons, especially capturing the flow physics present in separated regions. However, these methods are less developed compared to RANS, so groups are still working to learn and document best practices. For example, HRLES users are continually working to improve its “shielding function" that prevents LES from encroaching too far down into the boundary layer where RANS is desired. And WMLES advocates are trying to learn how to better handle the flow close to wing leading edges, where it is difficult to predict transition and to sufficiently resolve turbulent eddies within the very thin boundary layers there. Also, there are many different ways to implement HRLES and WMLES; there is yet to be a trend downselecting toward only a few “best" methods. Currently, the many different methods available are competing for attention.

Although there have been some efforts to incorporate transition and/or the wind tunnel geometry into CFD solutions, for the HLPWs the computations have mostly been fully turbulent and free air (compared with corrected wind tunnel data). Future workshops will probably have more focus on these challenges, in spite of the fact that doing so will likely make it even more difficult for CFD to achieve consistency between different codes/methods. Additionally, up to the current time, the HLPWs have not directly addressed aeroelasticity. Typically the high-lift wind tunnel test articles have been relatively stiff, and CFD analysis has shown aeroelastic effects to be fairly insignificant [39]. However, the largest influence of these effects are likely to be near $C_{L,max}$, so it may be useful to explore them further in a workshop setting.

We have described the trend of scale-resolving simulation methods replacing RANS for predicting high-lift flowfields near stall, particularly when getting the right answer for the right reasons really matters. What are the prospects for future improvements in RANS models that could also accurately capture separated flow physics? So-called data-driven “machine learning" methods have arisen in recent years that have offered the hope of improved turbulence modeling [40]. However, to date these methods tend to be restricted to predicting flows that are very similar to those for which the improved models have been trained. High-lift configurations are so complicated, with so many different flow features involved, often interacting with each other, that it seems unlikely that a machine-trained model could improve CFD predictions in a general way any time in the near future. It is also not clear if RANS itself has already hit an “ultimate barrier" when it comes to predicting separated flows [41]. If so, then scale-resolving simulation methods may be the only way forward, because hit-or-miss attempts using RANS tweaks and attempted improvements would likely not generalize well.

There is clearly a strong, growing interest in accurate CFD predictions of high-lift flows. Over the course of the first four workshops, the participation has more than doubled from 21 to 44 groups, from as many as 17 countries. The number of CFD submissions has more than quadrupled from 39 to 184. Some of this interest is probably because high-lift flows occur during every aircraft flight (at takeoff and landing as well as during certain maneuvers), and accurate CFD prediction of this regime will be a necessary component of certification by analysis [42]. No doubt improved CFD capability in this area would help to reduce the cost of designing and bringing new airplane concepts to market. High-lift validation using the CRM-HL configuration has also become the focus of a broad “ecosystem" of international collaborative wind tunnel testing. With all of the attention and (eventual) wind tunnel data available for comparison, many CFD groups are keen to see how their results compare, and to be on the leading edge of new computational developments that arise from the collaboration.

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6. Copyright Statement

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