Wall-modeled large-eddy simulation of aircraft in landing configuration

By K. Goc, S. T. Bose and P. Moin

1. Motivation and objectives

The evaluation of scale-resolving computational fluid dynamics paradigms such as wall modeled large eddy simulation (WMLES) in the characterization of separated flows at high Reynolds numbers is motivated by the deficiency of Reynolds-averaged Navier-Stokes (RANS) in the simulation of such flows. The accuracy of RANS in the characterization of such flows has plateaued. The scatter in the results of the Third AIAA High Lift Prediction Workshop (HiLiftPW-3) shown in Figure 1, particularly near the stall flight condition, corroborates this claim (Rumsey et al. 2018). A variety of gridding and turbulence modeling approaches were employed as part of this workshop, with the most popular choice being the Spalart-Allmaras (SA) model on an unstructured grid with prismatic boundary layer elements blended to anisotropic tetrahedra in the far field. The average grid size was $\sim 62$ million control volumes (Mcv). The high degree of scatter near the stall flight condition tempers confidence in the predictive capability of steady RANS technology in the context of separated flows over complex geometries. Our objective is to evaluate the performance of WMLES in the characterization of the flow around an aircraft in landing configuration. WMLES is an emerging CFD paradigm (in the context of the simulation of flows over complex geometries) that is well suited for the simulation of separated flows (Bose & Park 2018). One reason for its suitability is that WMLES is a time-accurate tool that directly resolves energy-containing turbulent motions, while the dissipative effect of subgrid-scale turbulent motions, which tend to be more universal, is modeled. Steady RANS, in contrast, solves directly for the mean flow while modeling all of the turbulent motions, including those that are energy containing and those that are dissipative. The direct resolution of energy-containing turbulent motions comes with added computational expense, though the cost of WMLES calculations carried out as part of this work is comparable to that of some RANS calculations of the same configuration, $\sim 45,000$ core-hours (Rumsey et al. 2018).

The NASA CFD Vision 2030 report has identified WMLES/WRLES for complex 3D flows at appropriate $Re$ as one of the technology milestones along the technology development roadmap it proposes. The milestone has an associated date of 2020 and appears to be a pacing item along the technology readiness maturation trajectory of WMLES (Slotnick et al. 2014). The WMLES calculations detailed in this report are of such a complex flow at an appropriate Reynolds number ($Re = 1.93 \times 10^6$). The evaluation case considered is that of the JAXA Standard Model (JSM), a high-lift aircraft model featuring the geometric complexity of deployed control surfaces with slat brackets and flap support fairings. The use of turbulence-resolving paradigms, including delayed-detached eddy simulation (DDES) by Cary et al. (2018) and lattice-Boltzmann methods (LBM) by Konig et al. (2016), in the simulation of the flow around this configuration has led to an improved characterization of quantities of interest (i.e. $C_L$ vs. $\alpha$, $C_p$ vs. $x/c$) near the stall flight condition, indicating that resolution of turbulent motions in the near-wake is
Figure 1. JSM nacelle/pylon off lift curve. Circles represent data from the experimental test campaign, while lines are computational results submitted by participants of AIAA HiLift-PW3. The majority of the submissions to the workshop were RANS calculations, with select DDES and LBM results (Rumsey et al. 2018). A high degree of scatter is observed in the results, particularly around stall.

Figure 2. Floor-mounted half-span JAXA Standard Model in the JAXA 6.5 m × 5.5 m LWT1.

an important factor in the prediction of aircraft maximum lift. We have compared the predictions of WMLES to the results of an experimental test campaign conducted in the JAXA Low-Speed Wind Tunnel (LWT1) (Yokokawa et al. 2008). The wind tunnel model is a half-span model mounted on the tunnel floor with a 70 mm offset, sized to enforce an equivalence between the effective aspect ratio (a ratio of the lift coefficient squared to the drag coefficient) of the wind tunnel model and the effective aspect ratio predicted by free air RANS calculations (Yokokawa et al. 2010). The floor-mounted model is shown in Figure 2. Sensitivity to wind tunnel effects is evaluated via the inclusion of the test section geometry, including the tunnel side walls and 70 mm offset, in the WMLES calculations. Our simulations have leveraged the second-order finite volume code CharLES (Cascade Technologies, Inc.) with Voronoi grids (Ham et al. 2006).
2. Wall modeling and subgrid-scale modeling

The Vreman model with constant model coefficient (Vreman 2004) is used to model the subgrid-scale stresses in the present work. The term wall model refers to the (often) RANS-based model that is introduced between the wall and the log layer to provide wall stresses and heat fluxes to the outer-flow LES, which is under-resolved near the wall. These are imposed by means of a Neumann boundary condition on velocity and temperature obtained by solving some approximation to the RANS equations in the thin region between the wall and the LES/RANS exchange location. The wall modeling procedure is depicted in Figure 3. Viscous stresses are modeled using a RANS-based formulation with an equilibrium stress approximation, meaning that the sum of the viscous and turbulent stresses is assumed to be invariant between the wall and the LES/RANS exchange location. Equilibrium wall modeling (EQWM) approaches, such as that of Kawai & Larsson (2012), solve a system of two coupled ordinary differential equations derived from the turbulent boundary layer equations in the wall-normal direction, the solutions of which are the velocity and temperature profiles. The turbulent eddy viscosity is introduced to model the nonlinear term in the equation and is computed via a mixing-length hypothesis with a length scale based on the wall distance. A Van Driest-type damping is typically applied such that the turbulent stresses vanish near the wall with the right asymptotic behavior. The effect of non-equilibrium terms (pressure gradient, convective, and unsteady) is neglected in the wall model, though their effect is argued to enter implicitly into the wall model through the LES flow field. Improved agreement has been observed from the explicit inclusion of non-equilibrium terms in the wall model in a canonical bump flow (Park 2017). The extension of such models to complex configurations is a current area of research (Park & Moin 2014).

In the present work, a significant speedup is achieved in the time integration of the governing equations by neglecting non-equilibrium effects and by assuming a form of the damping of the eddy viscosity that allows for the EQWM equations to be solved analytically, as detailed by Wang & Moin (2002). In this case, the wall model equations reduce to algebraic equations for the wall stresses which can be solved efficiently with a Newton-Raphson root finding algorithm. CharLES contains the algebraic wall model implementation shown in Eq. (2.1), which recovers the linearity of the velocity profile in the viscous sublayer and the logarithmic character of the profile off the wall.

\[
  u^+(y^+) = \begin{cases} 
    y^+ + a_1(y^+) & \text{for } y < y^* \\
    \frac{1}{\kappa} \ln(y^+) + B & \text{otherwise,}
  \end{cases}
\]  

(2.1)

In Eq. (2.1), \( \kappa = 0.41 \), \( B = 5.2 \), \( y^* \approx 23 \), and \( a_1 = \frac{1}{2y^*}(\frac{1}{\kappa y^*} - 1) \). The value of \( a_1 \) is chosen to enforce the \( C^1 \) continuity of the velocity profile. The CharLES code showed no appreciable sensitivity to time-filtering of the LES flow field at the LES/wall model exchange location in a high Reynolds number turbulent channel flow, a technique known to ameliorate the log-layer mismatch problem in WMLES calculations. Log layer mismatch is a phenomenon that causes a 10-15% shift in the log-layer velocity profile, potentially due to the artificial correlation between the LES velocity at the exchange location and the wall stress that is introduced by the coupling of these two quantities through the wall model (Yang et al. 2017). Since log layer mismatch has not been observed in a channel flow at high Reynolds number using this code, we choose to fix the LES/wall model exchange location at the first grid point and do not implement time filtering for any of the calculations detailed in this report.
Figure 3. Schematic of the wall modeling procedure. The schematic generalizes to various types of RANS-based wall modeling, including non-equilibrium wall modeling (NEQWM) and equilibrium wall modeling (EQWM) (Kawai & Larsson 2012).

3. Geometry and spatial discretization

The computer-aided design (CAD) geometry used in the present study is shown in Figure 4. The JAXA low-speed wind tunnel test section is reproduced exactly, including the 70 mm peniche/sealant tunnel wall offset and the tunnel side walls. The computational domain is extended ∼4 fuselage lengths upstream and downstream of the test section to mitigate numerical contamination from the inlet/outlet. It is worth noting that a 70 mm offset is used in the experiment in the force computations, while a 40 mm offset is used for the oil flow visualizations. Sensitivity of the flow field to the offset height is detailed by Yokokawa et al. (2010) and is generally small over this range of offset heights. The cross sectional area of the test section grows to account for model blockage. The domain is spatially discretized by means of the gridding module (Stitch), native to the CharLES flow solver suite. Slices of the grid are shown in Figure 5. Isotropic hexagonal close-packed cells are generated by computing the Voronoi diagram associated with a staggered point seeding in the domain. The Voronoi diagram associated with a given point seeding is unique once the seed points are defined. Each control volume contains the locus of space that is closer to that seed point than to any other seed point. Lloyd’s algorithm is used to move the Voronoi seed points towards the cell centroid of each control volume (Du et al. 2006).

4. Results

4.1. Forces and moments

The six angles of attack that are evaluated as part of this study coincide with the angles that were requested of the participants of HiLiftPW-3. Three of these angles are in the linear region of the lift curve, while the other three are before, at, and after $C_{L_{\text{max}}}$. Both free air calculations and calculations that include the wind tunnel geometry have been carried out. The inclusion of wind tunnel geometry mitigates some of the uncertainty associated with wind tunnel corrections, which are not as robust for a tunnel floor-mounted half span model as they are for a strut or sting-mounted full-span model. The wind tunnel corrections employed in the experimental test campaign are those of Barlow et al. (1999). Calculations that include the wind tunnel walls and half-model mount are
Figure 4. CAD geometry of the JSM in the JAXA LWT1.

to be compared with uncorrected experimental data, while free air calculations should be compared with corrected experimental data. The lift curve predicted by WMLES is in good agreement with experimental force balance measurements obtained near stall, as shown in Figure 6. Each data point is obtained by averaging the forces for the last 20 flow pass times (the time it takes a fluid parcel to travel a distance equivalent to one mean aerodynamic chord) of a calculation that is integrated for a minimum of 30 flow pass times. This interval is selected to mitigate the impact of start-up transients associated with a calculation that is cold-started. The trend associated with wind tunnel corrections is captured in the linear region of the curve. More discussion on the results of a calculation in the linear region and in the post-stall region is included in the next subsections. The drag polar is shown in Figure 7. Over-prediction of the drag is observed across the entire $\alpha$ range. This finding is consistent with the results of HiLift-PW3. An inset graphic in Figure 7 shows the drag predictions from all participants of this workshop, showing a systematic over-prediction of drag, suggesting that this is not a useful test case for validation of drag prediction. For the purpose of drag prediction, the community prefers the NASA Common Research Model (Levy et al. 2013). The pitching moment coefficient is shown as a function of angle of attack in Figure 8. This curve gives insight into how the lift is distributed along the span of a swept wing. Negative pitching moment is nose-down, while positive moment is nose-up. A CFD-predicted moment that lies above the experimental curve indicates too little nose-down moment, consistent with a swept wing whose inboard section is too strong relative to the outboard section. The trend associated with wind tunnel effects, i.e., less nose-down moment at high $\alpha$ compared to the corrected free air pitching moment, is predicted by WMLES.

4.2. Post-stall angle of attack

Sectional pressure measurements at a post-stall angle of attack of 21° shown in Figure 9 corroborate the accuracy of the force predictions at this condition. WMLES can capture the trend associated with wind tunnel corrections at a post-stall angle of attack. Various types of flow separation, including geometrically imposed separation from a slat bracket and separation of the juncture flow at the wing root, are predicted. The calculations reveal
sensitivity to wind tunnel effects, particularly at the penultimate outboard slat bracket and at the wing root. There is evidence that WMLES predicts the trend associated with wind tunnel effects, as separation from the penultimate slat bracket is suppressed and a weakened inboard wing (deeper blue skin friction contour, indicative of a flow closer to separation) is observed in the WMLES calculations that include wind tunnel geometry. Four million extra grid points in the wind tunnel calculations are used to resolve the tunnel floor boundary layer, which is shown to be in reasonable agreement with the experimentally reported boundary layer thickness (Ito et al. 2019) in Figure 12 measured at a streamwise plane coincident with the model rotation center. Resolution off the airplane surface is identical between the free air and wind tunnel calculations despite the different cell count (due to the tunnel sidewall resolution). The wall model is applied everywhere (on the airplane and on the tunnel sidewalls). The case shows a favorable response to targeted grid resolution added at the leading edge of the main element and on the upper surface of the slat, where the boundary layers are the thinnest. The skin friction from the case with targeted leading edge resolution is visualized in Figure 10 by means of skin friction streamlines, which show a reversal of the mean flow in the upstream direction near the wing root. Forces from this case are not reported because the case was not integrated far enough to reach a statistically converged state due to computational resource limitations. A pseudo-Schlieren of the flow at the post-stall angle of attack is shown in Figure 11, with relevant flow features identified. Of note are the separated flow behind the most outboard slat bracket, a wingtip vortex, disturbed flow behind the slat brackets, and a fuselage vortex, whose presence has been previously observed in
4.3. Linear region of lift curve

Investigation of the over-prediction of lift at a low angle of attack has been carried out by means of adding targeted grid resolution on the trailing edge flaps. The flaps are most highly loaded at a low model angle of attack, a phenomenon observed in the experimental work of Chin et al. (1993). For this reason, the flaps are a good candidate for additional resolution, particularly because the experimental oil flow visualization shown in Figure 13 shows separation in the flap support fairing wake and at the flap/body juncture that is missing in the baseline calculation. There is some sensitivity of the results to targeted flap resolution. The flap support fairing wakes and the juncture separation patterns appear in the projection of first cell velocity visualizations shown in Figure 13, though the
Figure 8. JSM moment coefficient. WMLES predicts the trend associated with wind tunnel corrections, but not the magnitude of the correction.

Figure 9. Comparison of the flow pattern from the JAXA experimental test campaign (as visualized by fluorescent oil) to average skin friction contours from WMLES, including from a calculation that includes wind tunnel geometry and a free air calculation.

Figure 10. The WMLES calculations respond well to targeted grid refinement of the leading edge of the mean element and of the upper surface of the slat, where the boundary layer thickness is lowest. Shown above are streamlines of skin friction computed from a calculation run on a refined grid numbering 125M cells. A reversal of the flow in the upstream direction at the wing root near the trailing edge of the main element is visible, indicating flow separation.
WMLES of aircraft in landing configuration

Figure 11. Pseudo-Schlieren visualization of the flow over the JSM at a post stall angle of attack with wind tunnel geometry included in the calculation. Salient flow features are identified, including a fuselage vortex, slat bracket wakes, outboard separation, and the wingtip vortex.

Figure 12. WMLES calculation of the JSM in the LWT1 wind tunnel test section showing contours of the first cell velocity magnitude in grayscale. Half of the test section enclosure is blanked for visualization purposes. Measurement of the boundary layer thickness at a streamwise location coincident with the model rotation center reveals good agreement with the quoted $\delta_{99}$ of 140 mm.

global forces show little response to this resolution exercise. The evaluation of sectional pressures at the experimentally reported locations along the semi-span of the wing is shown in Figure 14. The results from a calculation with targeted flap refinement are overlayed on the results from a baseline calculation. There is no evidence of a systematic
Figure 13. Free air calculations at 4.36° show the effect of targeted refinement of the flaps. There is evidence that flap resolution leads to an improved characterization of the separation patterns behind the flap support fairings (dotted circle) and from the flap-body juncture (dashed circle) that were observed in the oil flow visualizations from the experiment.

Figure 14. Sectional pressures from WMLES at six pressure belts along the semi-span of the wing reveal good agreement with experiment. Belt locations are measured as a fraction of the wing semi-span. Free air calculations at 4.36° are compared with uncorrected wind tunnel measurements at 4°. Little sensitivity to flap resolution is observed, in contrast to the flow visualization of Figure 13, potentially due to under sampling of regions with flow separation by the pressure belts.

Over-prediction of upper surface suction by the WMLES that would account for the over-prediction in lift force. This is a topic for further investigation, potentially by means of exploring the sensitivity of the results to the resolution of the fuselage vortex, which contributes to the force in the lift direction.
5. Conclusions

We have shown that WMLES with an equilibrium wall model and a modest number of grid points $O(10^7)$ can predict quantities of interest ($C_L$ versus $\alpha$, $C_p$ versus $x/c$) for high Reynolds number flows over a realistic geometry at reasonable cost. Each angle of attack cost $\sim 800,000$ core-hours for a simulation time horizon of 30 convective time units (equal to the time it takes a fluid parcel to travel a distance equivalent to the length of the mean aerodynamic chord). The cost of the integration of 30 time units is not sensitive to the angle of attack for a given grid size. When converted to an equivalent cost on an Intel (circa 2016) architecture, this cost translates to $\sim 45,000$ core-hours, meaning that one could get an answer overnight given access to 4,000 cores on a high-performance computing resource. WMLES can characterize the lift curve around the stall flight condition of the JSM. Comparison of sectional pressures along the semi-span of the wing at a post-stall angle of attack suggests that the lift curve prediction agrees with the experimentally measured curve for the right reasons. Moreover, WMLES can capture trends associated with wind tunnel corrections. Comparison of experimental oil flow images with WMLES surface skin friction contours reveals a qualitative agreement between separation patterns from a WMLES calculation that includes the tunnel geometry and the experiment. Geometrically-imposed separation from an outboard slat bracket and separation of the juncture flow at the wing root are observed in the experiment and in the calculation. The findings of this investigation suggest that WMLES is a tool capable of informing engineering decisions involving problems of external aerodynamic flows at high Reynolds numbers.

Acknowledgments

This investigation was funded by NASA and Boeing Research & Technology. Supercomputing resources were provided through the Department of Energy’s INCITE Program.

REFERENCES


