Fully-automated high-fidelity LES around high-lift aircraft configuration near stall

Hiroyuki Asada* and Soshi Kawai*
Corresponding author: h.asada@tohoku.ac.jp
* Department of Aerospace Engineering, Tohoku University, Japan.

Abstract: High-fidelity wall-modeled LES around high-lift aircraft configuration near stall condition is presented. The key numerical methods of the present wall-modeled LES are the hierarchical Cartesian grid, the wall-modeling on a non-body-conforming Cartesian grid, and the stable and non-dissipative kinetic energy and entropy preserving (KEEP) scheme. The number of cells is 20.5 billion cells and the supercomputer "Fugaku" is used for massively parallel computations. The present wall-modeled LES is robust and successfully predicts the complex flows (separated flow pattern, pressure distribution, and lift coefficient) around high-lift aircraft configuration near stall. Additionally, the advantage of the non-dissipative nature of the KEEP scheme compared to the conventional upwind scheme is demonstrated on the present wall-modeled LES.

Keywords: LES, hierarchical Cartesian grid, stable and non-dissipative schemes, high-lift aircraft.

1 Introduction

This study presents high-fidelity wall-modeled large-eddy simulations (LES) around high-lift aircraft configuration near stall at high Reynolds numbers. The present wall-modeled LES is realized by three key numerical methods – the hierarchical Cartesian grid, the wall-modeling on a non-body-conforming Cartesian grid [1], and the kinetic energy and entropy preserving (KEEP) scheme [2]. The hierarchical Cartesian grid gives a fast and fully automated grid generation even for the complex aircraft geometries. The wall-modeling substantially reduces the number of grid points required for resolving inner-layer turbulence, which enables the LES of high Reynolds number flows. Additionally, our group developed the wall-modeling for the hierarchical Cartesian grid to realize wall-modeled LES around complex geometries at high Reynolds numbers [1]. The KEEP scheme [3] is stable and non-dissipative and thus is suitable for high-fidelity simulations. The KEEP scheme achieves superior numerical stability with zero numerical dissipation by significantly improving the kinetic energy preservation and entropy preservation at the discrete level. Furthermore, to handle the complex geometries, the KEEP scheme on the hierarchical Cartesian grid was also developed in our group [2]. This paper highlights the significant advantage of the KEEP scheme and demonstrates the feasibility of the high-fidelity wall-modeled LES of complex flows around high-lift aircraft configuration.

2 Flow conditions and results

The aircraft configuration simulated in this study is the JAXA standard model (JSM) which consists of the wings, a fuselage, engine nacelles, high-lift devices (slat and flap), and supports of the high-lift devices. The freestream Mach number is $M_\infty = 0.172$, the Reynolds number based on the mean aerodynamic chord is $Re_c = 1.93 \times 10^6$, and the angle of attack is $\alpha = 18.58\,\mathrm{deg}$. Two hierarchical Cartesian grids with different refinement levels, Grid 1 (3.6 billion cells) and Grid 2 (20.5 billion cells), are generated as shown in Fig. 1. For the LES, massively parallel computations are performed using the supercomputer "Fugaku", and the

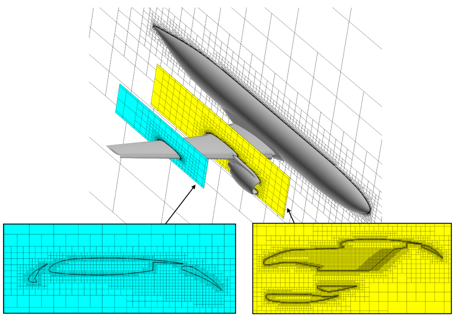


Figure 1: Hierarchical Cartesian grid around JSM.

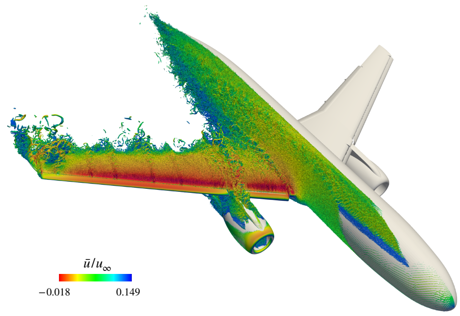
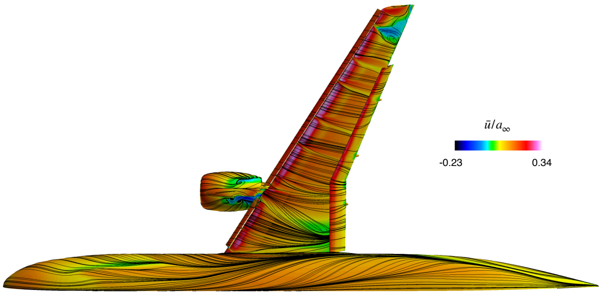
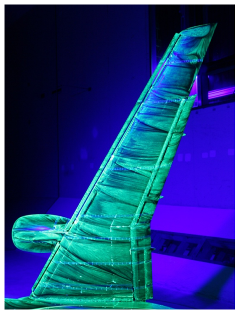


Figure 2: Iso-surfaces of Q criterion.



(a) Wall-modeled LES (present, Grid2, KEEP)



(b) Experiment (oil flow) [4]

Figure 3: Time-averaged streamline

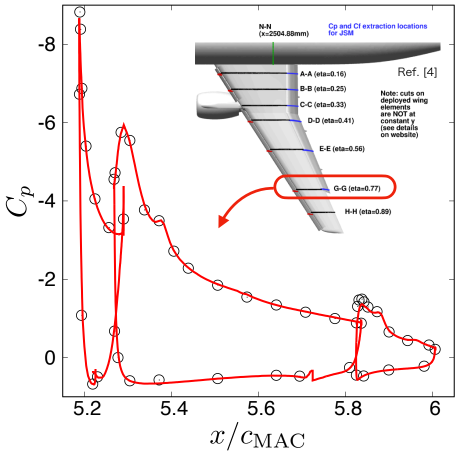


Figure 4: Time-averaged pressure coefficient C_p

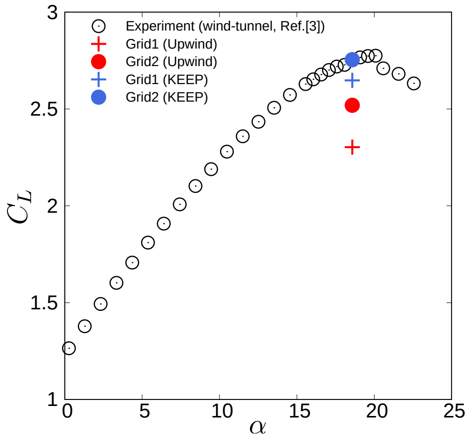


Figure 5: Lift coefficient C_L.

numbers of used nodes are 768 and 3,456 for Grid1 and Grid2, respectively (each node of Fugaku has 48 cores). The KEEP scheme and the upwind schemes are used for the spatial discretizations to assess the performances of the KEEP scheme.

This study successfully realizes the robust and high-fidelity wall-modeled LES around the high-lift aircraft configuration thanks to three key numerical methods mentioned above. Figure 2 shows the instantaneous Q criterion colored by streamwise velocity. The small vortex structures are simulated well near the walls as in the conventional LES. Figure 3 shows the time-averaged streamline obtained by the KEEP scheme with Grid2 along with the experimental data of oil flow [4]. The present wall-modeled LES predicts the attached inboard flow and the separated outboard flow, which agrees well with the experimental oil flow. The successful prediction of the outboard separation gives good agreements of the pressure distribution with the experimental data, as shown in Fig. 4. Note that, although not shown here, the upwind scheme with Grid2 erroneously predicts the separated inboard flow. Figure 5 shows the predicted lift coefficient along with the experimental data reported in the 3rd High Lift Prediction Workshop[4]. While the prior RANS results showed a significant spread for the present near-stall condition in the workshop, the wall-modeled LES with the KEEP scheme and Grid2 gives excellent agreement with the experimental data. Additionally, the lift obtained by the KEEP scheme with Grid1 gives better agreements with the experimental data than the lift obtained by the upwind scheme with Grid2, which highlights the advantage of the non-dissipative nature of the KEEP scheme.

3 Conclusion and Future Work

High-fidelity wall-modeled LES around high-lift aircraft configuration near stall condition is presented and the significant advantage of kinetic energy and entropy preserving (KEEP) scheme is demonstrated. In the future conference, we will present the detailed strategy of the KEEP scheme, the grid convergence study with results by Grid3 (100 billion cells), and wall-modeled LES at pre- and post-stall conditions ($\alpha = 10.47\,$deg and $21.57\,$deg in addition to $18.58\,$deg).

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