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Review Report

Current Status on Large-Eddy Simulation for Engineering Applications

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1. Introduction

The history of computer simulation for fluid dynamics dates to late 1970's, and for these past 30 years with the rapid development of computer technology, Computational Fluid Dynamics (CFD) has now achieved the status of the third analysis method, following to the theoretical and experimental analysis. In Japan, the then-world fastest (40 Teraflops) vector-processing parallel computing system, "Earth Simulator", started its operation in 2002, and since then, with rapid catch-up of USA to enhance their national prestige, the peak performance of supercomputers has been improved faster than ever. The supercomputer for the next generation with the performance of more than 10 Petaflops is now being planned in Japan, which will be born in 2011 if everything goes smoothly. The significant growth of the high-end supercomputers also boosts the performance of general-purpose computers, increasing the usefulness of computer simulation in various industries. Accordingly visualization techniques to treat the huge numerical results of High-Performance Computing (HPC) are becoming more and more important. In this review, we mention the brief history of Large-Eddy Simulation (LES) as the most promising turbulence simulation for engineering purpose and its state of the art technique from the viewpoint of its industrial use.

2. Progress on High-Performance Computing and Large-Eddy Simulation

The remarkable history of CFD has been supported by a few milestones relating to HPC technology. The first breakthrough was provided by the rise of vector-processor supercomputers in 1990's. The peak performance of *Gigaflops* at that time made it possible to conduct full three-dimensional unsteady simulation, and the transition from Reynold-Averaged Navier-Stokes (RANS) to LES was enhanced. The second one was caused by the progress of parallel-processor computers with *Teraflops* performance in the beginning of 2000, which contributed to the growth of Direct Numerical Simulation (DNS) and LES for engineering applications. Nowadays we can apply LES to engineering flows with complicated geometry, but difficulty of treating the boundary layer, which requires excessively high grid resolution at very thin region over a solid surface, restricts its use only at moderately low Reynolds number condition. An ad hoc solution was proposed for the difficulty by applying RANS method for the solid boundary condition of LES, which is called Hybrid RANS/LES method. The method is also called Detached Eddy Simulation (DES) by Spalart et al. in 1997 when applied to external flows or flows around solid bodies. The rise of *Petaflops* supercomputers for the next generation will get rid of the problem in LES, but at the moment DES is promising and energetic efforts are being made recently. The study for the development of Hybrid RANS/LES is especially active in Europe and the symposium was organized by ERCOFTAC (European Research Community on Flow, Turbulence and Combustion) in 2005.

3. Development of Subgrid-Scale Turbulence Modeling

As mentioned in the previous section, the rapid development of HPC technique contributes substantially to the advancement of LES technology, and LES is now in the phase of practical use in industries. The advantage of LES is it can capture the unsteady or transient feature of turbulence, which is not possible for RANS simulation. Another important feature of LES is that the effect of subgrid-scale (SGS) modeling becomes smaller as the grid resolution is improved, which is different from RANS method in which a turbulence model adopted is the main factor to determine the accuracy of a simulation. In other words, in LES we can obtain a better result as long as finer numerical grids are maintained. In fact, the number of studies relating to SGS modelling presented at domestic as well as international conferences or symposiums is declining over the last ten years or so. The background of the relative unpopularity of SGS modeling in academia is that users of LES in industries are going to realize that, owing to the price reduction of CPU for grid computing, increasing the grid number with all the computer's power and simple SGS model is much easier and faster than treating sophisticated and complicated SGS models, which is usually unstable requiring special knowledge of both numerical method and physics. Thus the most popular LES method in industry at the moment is still the simple eddy viscosity of the conventional Smagorinsky's model, which was proposed at the beginning of LES history, with the ad hoc dumping function near the wall. Another important thing of LES is that finite difference errors and errors caused by SGS turbulence model are comparable as long as the second order finite difference is adopted for space. The users of LES also realize the fact through their experience that the prospective performance of an advanced SGS model cannot be reproduced by lower order finite difference scheme, because such an advanced model is usually developed and optimized by Spectral method in a very simple flow configuration. Considering the fact that the engineering LES must treat flow with complicated geometry and thus lower-order finite difference or element method is the main tool, all the SGS models such as the dynamic model (Germano et al., 1991), the scale similarity model (Bardina et al., 1980), and the deconvolution model (Stoltz & Adams, 1999), which were once though to be promising, have a slim chance of getting a major seat for the next generation. Because all of these models utilize grid-scale turbulence near the cutoff wavenumber, which is contaminated by numerical errors if lower order discretization is adopted.

From a standpoint of the importance of numerical errors in LES, reconstruction of LES formulation seems to be promising through the unified methodology of treating SGS strategy and numerical methods together, and some models relating to this approach were proposed (e.g., Hughs et al., 2001). This new LES methodorogy is encouraging, but the researches are still in the early stage of developments and further steps must be taken to apply it to engineering problems.

Finally we would like to end this section by pointing out the importance of LES for multi-physics (multiphase flow, combustion, acoustics, etc.) applications. In many industrial applications multi-physics treatment is required, but RANS faces a difficulty in some situations, such as acoustic problems in which pressure fluctuations must be solved or combustion flows in which flame surface and small-scale turbulence strongly interacts. LES will be able to treat such a target better than RANS, but SGS strategy must take into account for the multi-physics in some cases. For this purpose, the Smagorinsky's zero-equation type eddy viscosity model is going to be replaced by the one-equation type model solving the transportation equation of SGS energy directly, which was first proposed by Shumann (1975).

4. Issues on Numerical Methods

Unstructured finite volume and element methods get an edge so far over various numerical methods for simulations of practical applications in industries. The validity of these methods is the flexibility of mesh and grid generation, in which we can allocate appropriate mesh at the specific region at the required resolution. While the drawback of these unstructured methods is their difficulty in adopting higher order schemes; hence special care should be made when we conduct DNS or LES by such a numerical method. Anyhow, their advantage for flows with complicated geometry overcomes the disadvantage, and they will play a leading role for a while in industries.

Various studies of higher order schemes are now being made for DNS and LES; some of them, which are especially promising for accurate LES, are the fully conservative scheme (Morinishi et at., 1998), and the modified compact scheme. However these higher order schemes are still far from practical application to HPC-LES for complicated geometry, and further studies should be made especially in the context of its compatibility to unstructured elements or parallel processing.

Other than LES using the finite volume or element methods, discretized vortex method and lattice Boltzmann method attract attention in some targets where unsteady turbulence characteristics are especially important. The validity of these methods is its simple and quick grid generation. In some industries where geometrical shapes of targets are quite complicated, the CFD users seem to choose their numerical methods from the viewpoint of costs required for grid generation. Such a situation occurs when the cost or man-hour for the pre-processing, such as adjustment of CAD data, simplification of surface geometry by the wrapping technology, and grid generation, exceeds the simulation time even in LES. The problems of these relatively minor (but having big potential) methods that should be overcome are; their application to flows with heat and mass transfer, and accuracy for boundary layer.

5. High-Performance Large-Eddy Simulation for Engineering Applications

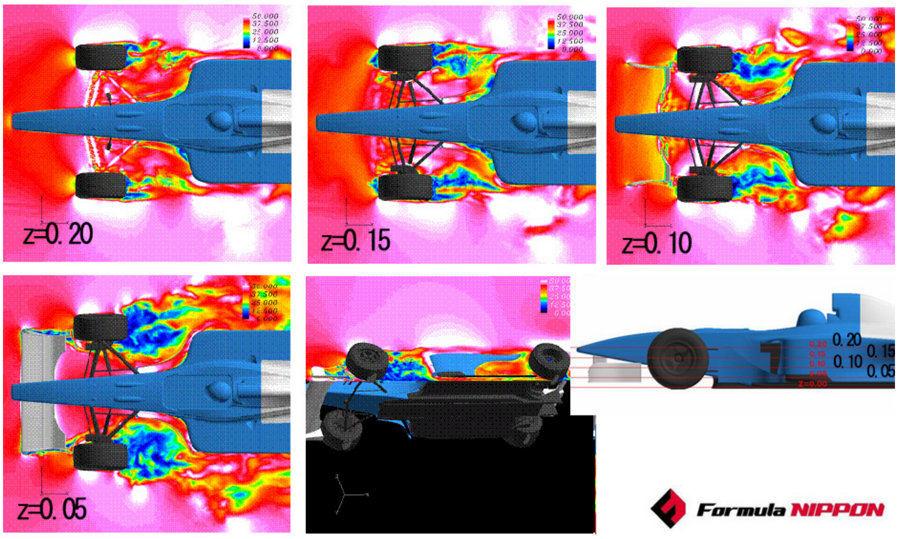

Fig. 1. Snapshots of the velocity distribution around front wheels of a formula car.

Two examples of the world's largest class LES for engineering applications are introduced to show the validity of numerical visualization; both of them were conducted on the Earth Simulator.

The first one is flow visualization around a formula car (Tsubokura et al., 2007), which is shown in Fig. 1. The unstructured finite volume software was used with about 120 million elements on 800 parallel processors. In a formula car, about 40 % of total drag is caused by the exposed wheels; especially in the front wheels, produced wake turbulence behind the wheels strongly interacts with car body and affects its aerodynamic characteristics. Accordingly understanding the unsteady or transient flow characteristics is important. The figures show the instantaneous velocity distributions around the wheels and the front wing at various heights from the ground. We can identify that wake turbulence are quite complicated and three dimensional, which consists of two wake features of rotating cylinder and rectangular cylinder.

The second one is numerical prediction of sound generated from flows in a multi-stage centrifugal pump (Kato et al., 2007). Prediction and reduction of the aerodynamic sound generated from eddies are crucial in various industrial applications such as fluid machinery, transport machinery, and ventilating facilities. LES is an ideal numerical method for the prediction because it can capture the unsteady flow fluctuations as the source of the noise. The major source of sound generated in such a pump is pressure fluctuations taking place on the interface of water and solid, which propagates as elastic waves in the solid part. The LES code adopted is based on the finite element formulations, and can treat the moving boundary interface with overset grids from multiple dynamic frames of reference. The total of 40 million elements are used in the simulation. Figure 2 indicates the instantaneous pressure fluctuations on the inner surface of the pump, which successfully visualizes the positions of sound source.

The both LES codes were developed at the University of Tokyo under the project of "Frontier Simulation Software for Industrial Science".

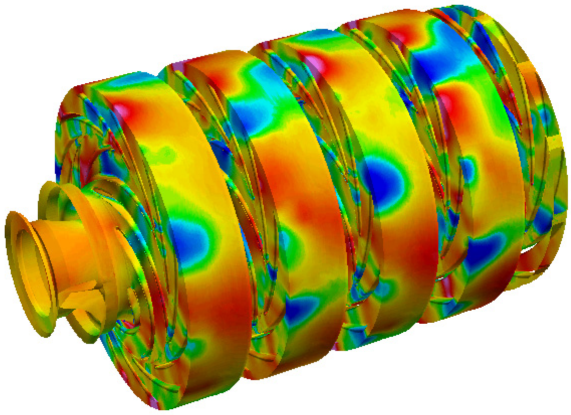

Fig. 2. Instantaneous pressure fluctuations for a multi-stage centrifugal pump.

6. Concluding Remarks

Current status of LES for engineering applications and validity of numerical visualization are reviewed. With its huge amounts of flow information included in three-dimensional unsteady flow field, LES will be undoubtedly the main tool for engineering fluid analysis within a couple of decades. The HPC technique is indispensable to conduct reliable engineering LES at present, but it should be noted that, considering the rapid development of hardware technology, the performance of the state of the art supercomputers at present will be available without difficulty in industries for practical use within a decade. The key of LES in practical use is not only the development of hardware (computer) and software (numerical method and turbulence model), but also the modification or the optimization for pre (grid generation) and post (visualization) processing methods. At least some tens to hundreds of elements are used for reliable engineering LES, but most of the commercial software for flow visualization, for instance, is unfortunately not well suited to treat such massive data. For the burst of practical use of LES, the burning issue will also be the improvement of such a surrounding technology for HPC-LES.

References

Bardina, J., Ferziger, J. and Reynolds, W., Improved subgrid-scale models for large-eddy simulation, AIAA Paper, 80-1357 (1980).

Germano, M., Piomelli, U., Moin, P. and Cabot, W., A dynamic subgrid-scale eddy viscosity model, Physics of Fluids A, 3 (1991), 1760-1765.

Hughes, T., Mazzei, L., Oberai, A. and Wray, The multiscale formulation of large eddy simulation: Decay of homogeneous isotropic turbulence, A., Physics of Fluids, 13 (2001), 505-512.

Kato, C., Yamade, Y., Wang, H., Guo, Y., Miyazawa, M., Takaishi, T., Yoshimura, S. and Takano, Y., Numerical prediction of sound generated from flows with a low Mach number, Computers and Fluids, 36 (2007), 53-68.

Morinishi, Y., Lund, T., Vasilyev, O. V. and Moin, P., Fully conservative higher order finite difference schemes for incompressible flow, J. Comput. Phys., 143 (1998), 90-124.

Schumann, U., Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli, Journal of Computational Physics, 18 (1975), 376-404.

Spalart, P. R., Jou, W.-H., Strelets, M. and Allmaras, S. R., Comments on the feasibility of LES for wings, and on a Hybrid RANS/LES approach", Proc. of the First AFOSR Int. Conf. on DNS/LES, (1997), 137-147.

Stolz, S. and Adams, N., An approximate deconvolution procedure for large-eddy simulation, Physics of Fluids, 11 (1999), 1699-1701.

Tsubokura, M., Kitoh, K., Oshima, N., Nakashima, T., Zhang, H., Onishi, K. and Kobayashi, T., Large eddy simulation of unsteady flow around a formula car on earth simulator, SAE 2007 World Congress, (2007), 2007-01-0106.

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