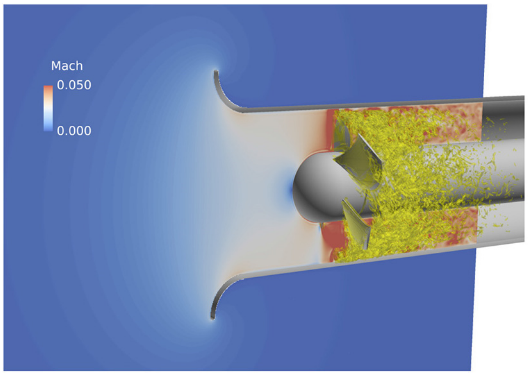
Development of High-fidelity CFD Tool for Aeroacoustics



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To improve the environmental performance of our products, Mitsubishi Heavy Industries, Ltd. (MHI) has taken on the challenge of reducing the noise from equipment. As part of these efforts, we are developing large-scale aeroacoustic noise analysis technology that enables the low-noise design of fluid equipment. Aeroacoustic noise analysis requires precise flow analysis and sound wave propagation analysis. From this perspective, the Lattice Boltzmann Method (LBM) has been applied as a large-scale fluid analysis technology that has been rapidly advancing in recent years and is of high potential. This report summarizes this analysis technology and presents the verification analyses of an aircraft airfoil during take-off/landing and axial fan noise.

1. Introduction

There are many types of fluid-related products in our portfolio. The long-distance propagation of pressure fluctuations caused by the interaction between these products and fluid may become a source of aeroacoustic noise. In product design, from the perspective of improving environmental performance, it is necessary to minimize the generation of such aeroacoustic noise from the product. Especially important in the design process is technology to predict the generation of aeroacoustic noise with high accuracy. In general, there are two prediction methods in this regard: wind tunnel test and computational fluid dynamics (CFD) analysis. The former is characterized by a long lead time from the production of a test piece that is exactly simulated in shape until data measurement in wind tunnel testing, which indicates difficulty in using it on a daily basis in the design process. The latter requires highly-accurate, large-scale CFD analysis, because unsteady turbulence can often be a source of aeroacoustic noise.

To enable highly-accurate, large-scale CFD analysis, MHI is developing a CFD analysis tool by employing the Lattice Boltzmann Method (LBM)(1). LBM is an analysis method in which the kinetic theory of gases is used as the analogy. It has been reported that, compared with conventional CFD analysis tools which are based on the Navier-Stokes equations, LBM requires a short turnaround time and its accuracy is high(2),(3). This report summarizes our LBM-based CFD analysis code and presents its characteristics and application examples.

2. CFD analysis tool development based on Lattice Boltzmann Method

LBM is a numerical algorithm in which fluid is approximated by a collection of many virtual particles with a velocity. The velocity distribution function of particles is used to compute the collision and translation of each particle and obtain the macroscopic flow field (e.g., flow velocity and pressure). Described below are the characteristics of our CFD analysis tool.

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(1) Cumulant collision model

As described earlier, it has been reported that LBM can perform fluid analysis within a shorter turnaround time and with higher accuracy than conventional CFD tools. When it comes to high-Reynolds-number flows, however, LBM analysis has a disadvantageous tendency to diverge. The flow fields of our products often involve flows with a high Reynolds number. To develop a practically-applicable CFD analysis tool, it is necessary to suppress numerical instability phenomena at high Reynolds numbers.

In our CFD analysis tool, the instability phenomena are suppressed by using the cumulant collision model(4). With this model, the numerical viscosity can be controlled at a level that does not directly affect the fluid governing equations, i.e., Navier-Stokes equations. It has thus become possible to analyze high-Reynolds-number flows in a stable manner.

(2) Wall model

Generally, the boundary layer near the wall surface is very thin. To resolve the boundary layer through CFD analysis, it is necessary to create a very dense analytical lattice near the wall surface. However, as LBM uses cubic lattice cells, it is difficult to locally change the lattice cell dimensions near the wall surface of any shape, thus resulting in an insufficient number of lattice cells near the wall surface.

As such, the equilibrium wall model(5) has been employed to capture the boundary layer near the wall surface in our CFD analysis tool, because it does not require a dense lattice near the wall surface.

(3) Moving boundary conditions

In consideration of application to rotating machinery such as fans, the boundary conditions for moving boundaries using the Multi-Direct Forcing Method(6) has been implemented in our analysis tool. In the Multi-Direct Forcing method, the wall surface of a moving body is regarded as a thin film and the external force term in the LBM equation is controlled in such a way that the desired moving velocity is realized on that thin film.

3. Verification and application to low-noise product design

As the verification of our CFD analysis tool and the application to low-noise product design, two case examples will be presented.

(1) Tool verification by aircraft airfoil analysis during take-off/landing

Described below are the results of aeroacoustic noise analysis of 30P30N three-element airfoil. It is an airfoil proposed openly as a CFD analysis benchmark problem at the Workshop on Benchmark problems for Airframe Noise Computations(7) (an international workshop to promote the improvement of airframe noise prediction technologies).

Figure 1 shows an example of unsteady flow field obtained by the analysis, i.e., Mach number distribution, which is a flow velocity indicator. In **Figures 2 and 3**, the wind tunnel test results are compared with the analysis results in terms of the pressure coefficient around the airfoil and the spectrum of unsteady pressure fluctuations, respectively. These figures show that the analysis results captured the complex flow field with large vortices. It has also been verified that pressure fluctuations, which will become a source of aeroacoustic noise, can be quantitatively assessed with high accuracy.

(2) Application to axial fan

The following are the results of aeroacoustic noise analysis with the use of USI7(8). It is a widely-known type of axial fan designed by the University of Siegen.

Figure 4 gives an example of the unsteady flow field obtained by the analysis (i.e., distribution of the divergence of velocity field, which is strongly correlated with the sound wave density disturbance). **Figure 5** shows the far-field Overall Sound Pressure Level (OASPL). It has thus been verified that aeroacoustic noise can be predicted to a high degree of accuracy even in application to fan rotation.

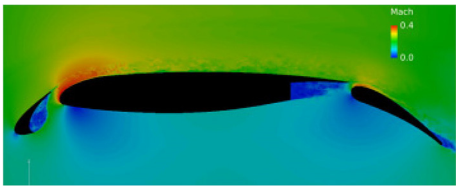

Figure 1 Example of flow field analysis of aircraft airfoil during take-off/landing - visualization of unsteady flow field

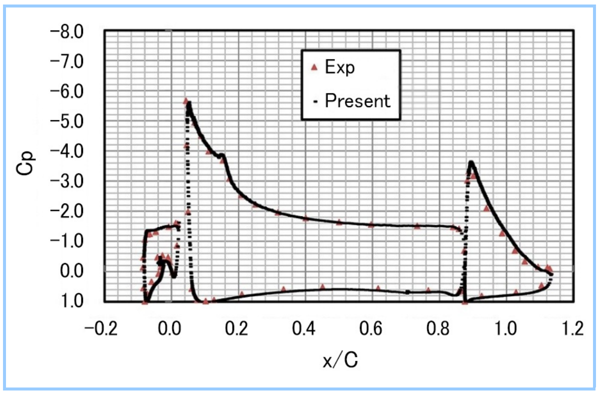

Figure 2 Example of flow field analysis of aircraft airfoil during take-off/landing - graph of pressure coefficient around airfoil

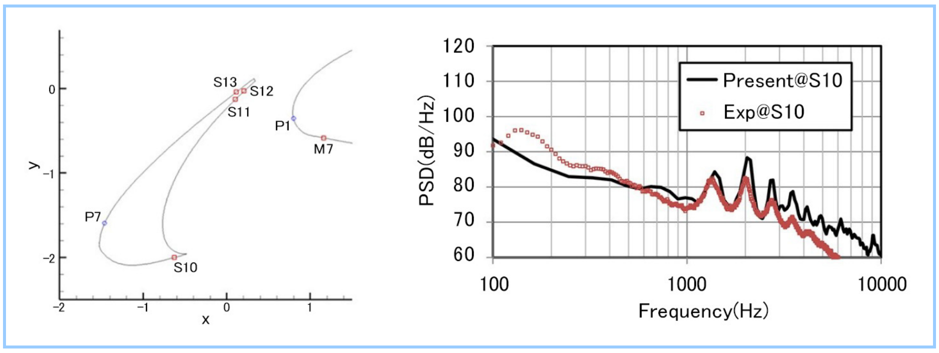

Figure 3 Example of flow field analysis of aircraft airfoil during take-off/landing - graph of unsteady pressure fluctuation spectrum

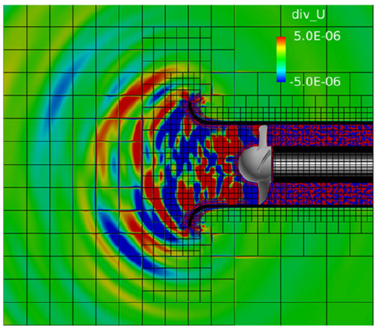

Figure 4 Example of flow field analysis of axial fan - visualization of aeroacoustic noise propagation

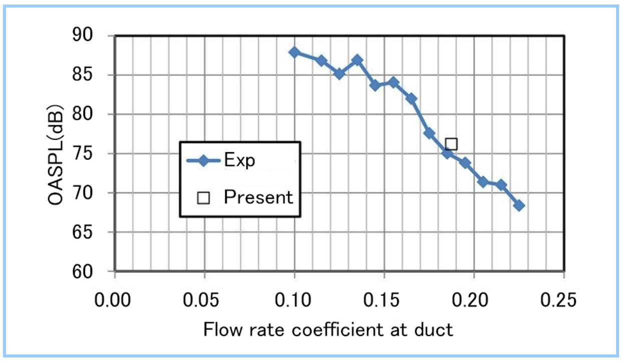

Figure 5 Example of flow field analysis of axial fan - OASPL graph

4. Conclusion

To improve the environmental performance of our products, we are working on the noise reduction of each type of equipment. This report summarizes the large-scale aeroacoustic noise analysis technology that enables the low-noise design of fluid equipment and presents the verification analyses of an aircraft airfoil during take-off/landing and axial fan noise. This analysis technology can accurately predict the generation of aeroacoustic noise and therefore is of use in examining noise reduction measures. By widely applying this technology to our products and taking appropriate measures for each type of equipment, we will further contribute to the noise reduction of each product.

References

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