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Large-Eddy Simulation of Hypersonic Configuration Aerodynamics

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***Abstract*—**LES with mixed subgrid-scale model has been used to simulate aerodynamic performance of hypersonic configuration. The simulation was conducted to replicate conditions and geometry of a model which has been previously tested. LES Model has been successful in predict pressure coefficient with the max error 1.5% besides afterbody. But in the high Mach number condition, it is poor in predict ability and product 12.5% error. The calculation error are mainly conducted by the distribution swirling. The fact of poor ability in the high Mach number and afterbody region indicated that the mixed subgrid-scale model should be improved in large eddied especially in hypersonic separate region. In the condition of attach and sideslip flight, the calculation results have waves. LES are successful in the prediction the pressure wave in hypersonic flow.

***Keywords*—**Hypersonic, LES, mixed Subgrid-scale model, experiment.

I. Introduction

AERODYNAMICS simulation is an important subject in hypersonic vehicle design. It is possible, in theory, to directly resolve the governing equations (Navier-Stokes equations) of turbulent flow using direct numerical simulation (DNS) in aerodynamics simulation. However, DNS is not feasible for practical engineering problems especially in hypersonic flows[1]. Two alternative methods can be employed to transform the Navier-Stokes equations in such a way that the small-scale turbulent fluctuations do not have to be directly simulated: Reynolds averaging and fltering. Both methods introduce additional terms in the governing equations that need to be modeled in order to achieve closure. The Reynolds-averaged Navier-Stokes(RANS) equations represent transport equations for the mean flow quantities only, with all the scales of the turbulence being modeled. The Reynolds-averaged approach is generally adopted for practical engineering calculations, and uses models such as Spalart-Allmaras, and its variants, and its variants, and the RSM. LES provides an alternative approach in which the large eddies are computed in simulation that uses a set of fltered equations[2]. Filtering is essentially a manipulation of the exact Navier-Stokes equation store move only the eddies that are smaller than the size of the filter, which is usually taken as the mesh size. A lot of works of the LES application to aerodynamics simulation have been done. However, the key feature of LES should be validation by experiment.

The present work is an ongoing effort to develop accurate flow simulation of hypersonic vehicle. In this paper, experiment and three dimensional calculation of a hypersonic configuration have been conducted. The purpose of this work is to test the ability of LES in hypersonic simulation.

II. Governing Equations

The governing equations of air flow are given in the flowing by mass, momentum, energy conservation equations.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_j)}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i u_j + p\delta_{ij} - \sigma_{ji}\right)=0 \tag{2}$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial}{\partial x_j}\left((\rho E + p)u_j + q_j - \sigma_{ij}u_i\right)=0 \tag{3}$$

The governing equations employed for LES are obtained by filtering the Navier-Stokes equations. Filtered variable is defined by

$$\bar{f}(x)=\int_D f(x')G(x,x';\bar{\Delta})dx' \tag{4}$$

Where D is the entire flow domain
G is the filter function
$\bar{\Delta}$ is the filter-width

In this paper, we defined filter function as

$$G(x,x')=\begin{cases}1/V, x'\in v\\ 0, x'\notin v\end{cases}$$

V is the volume of a computational cell
v is the computational cell domain

Applying filtering operation, we can obtain LES governing equations.

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho \bar{u}_j\right)=0 \tag{5}$$

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$$\frac{\partial(\rho\bar{u}_i)}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho\bar{u}_i\bar{u}_j+\bar{p}\delta_{ij}-\bar{\sigma}_{ji}\right)=-\frac{\partial\tau_{ji}}{\partial x_j} \quad (6)$$

$$\frac{\partial\rho\bar{E}}{\partial t}+\frac{\partial}{\partial x_j}\left((\rho\bar{E}+\bar{p})\bar{u}_j+\bar{q}_j-\bar{\sigma}_{ij}\bar{u}_i\right)=-\frac{\partial}{\partial x_j}\left(\gamma C_V Q_j+\frac{1}{2}J_j-D_j\right) \quad (7)$$

Where $\bar{\sigma}_{ij}=2\mu\bar{S}_{ij}-\frac{2}{3}\mu\delta_{ij}\bar{S}_{kk}$ is the flow stresse

$$S_{ij}=\frac{1}{2}\left(\partial u_i/\partial x_i-\partial u_j/\partial x_i\right)$$

$\bar{q}_j=-\lambda\frac{\partial\bar{T}}{\partial x_j}$ is thermal conductivity

$\tau_{ji}=\rho\left(\overline{u_i u_j}-\bar{u}_i\bar{u}_j\right)$is

the subgrid-scale stresses(SGSs) resulting from the filtering operation

$E=c_V T+uu/2$ is the total energy

$$J_j=\rho\left(\overline{u_j u_k u_k}-\bar{u}_j\overline{u_k u_k}\right)$$

$$D_j=\overline{\sigma_{ij}u_i}-\bar{\sigma}_{ij}\bar{u}_i$$

The detailed description of the LES governing equation can be found in reference [3].

III. Subgrid-Scale Models

Subgrid-scale model used in this paper is the mixed model proposed by Erlebacher and Zang[4].

$$\tau_{ij}=C_s\alpha_{ij}+A_{ij}-\frac{\delta_{ij}}{3}A_{kk}+\frac{1}{3}\tau_{kk}\delta_{ij}$$

Where

$$\alpha_{ij}=-2\bar{\Delta}^2\rho|\bar{S}|\left(\bar{S}_{ij}-\frac{\delta_{ij}}{3}\bar{S}_{kk}\right),|\bar{S}|=\left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2}$$

$$\tau_{kk}=C_I 2\rho\bar{\Delta}^2|\bar{S}|^2+A_{kk}$$

$$A_{ij}=\rho\left(\overline{\bar{u}_i\bar{u}_j}-\bar{\bar{u}}_i\bar{\bar{u}}_j\right)$$

$$C_S=0.16, C_I=0.09$$

IV. Simulation and Experiment

LES CFD simulations have been conducted using developed –in-house code .The most interesting development from this study concerned the CFD-based code computed for the aerodynamic model of a hypersonic configuration. An excellent reference is [5]. For the purposes to compare with the experimental data, simulation was conducted for the following conditions.

The model for calculation is listed in the following.

TABLE I
Simulation Conditions

Ma	Angle of attach	Angle of sideslip	Ma	Angle of attach	Angle of sideslip
4.937	0,4,8,12	0	5.993	4	4,8,12
5.993	0,4,8,12	0			
6.971	0,4,8,12	0			
4.937	0,4,8,12	0			

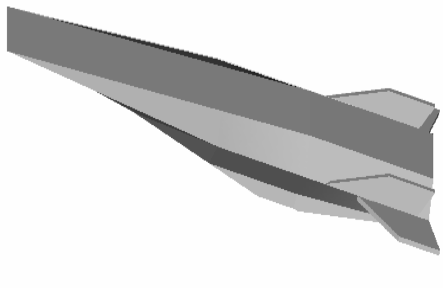

Fig. 1 The Calculation Model

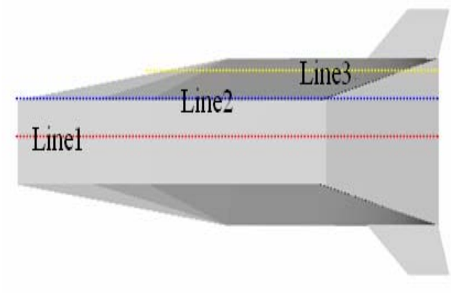

Fig. 2 The Monitor point for pressure

In the experiment, the pressures of the hypersonic configuration bottom surface are test in line1, line2 and line3 (showed in Fig. 2). So we just compare the calculation pressure with experimental data in these three lines.

The calculation grid and one of the results are listed in the following.

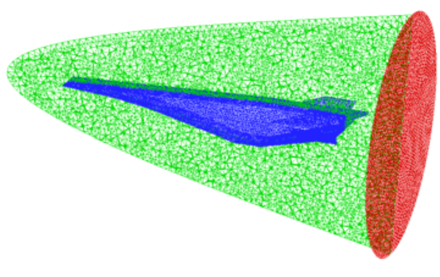

Fig. 3 Calculation grid

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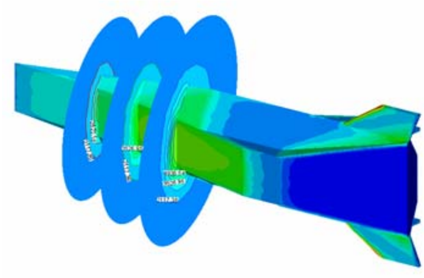

Fig.4 Pressure distribution from simulation

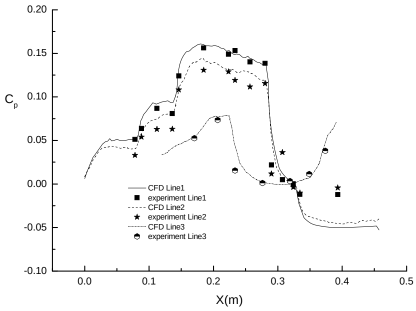

Fig.5 $Ma = 4.937 \alpha = 0 \beta = 0$

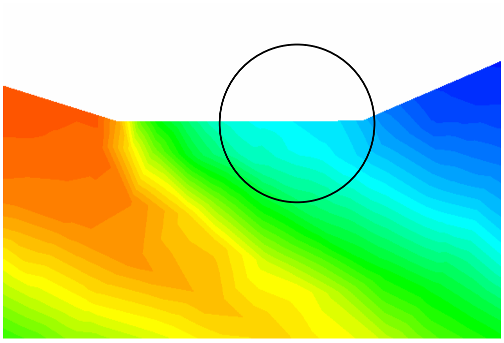

Fig.6 Pressure distribution at Ma=5

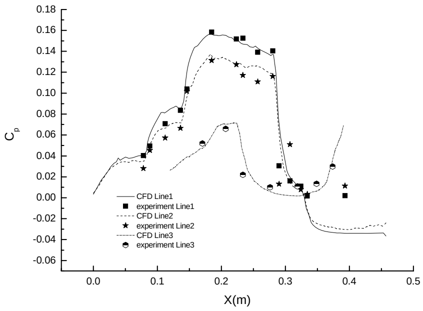

Fig.7 $Ma = 5.993 \alpha = 0 \beta = 0$

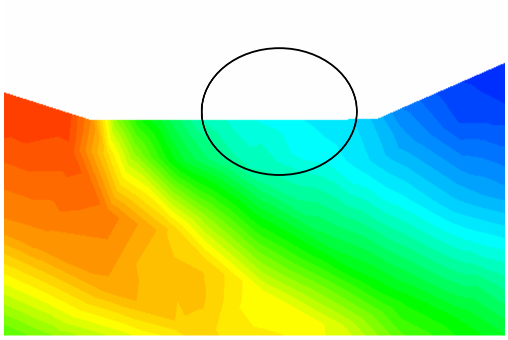

Fig. 8 Pressure distribution at Ma=6

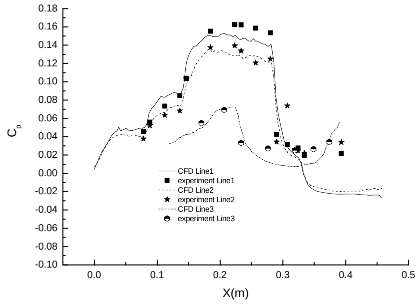

Fig. 9 $Ma = 6.971 \alpha = 0 \beta = 0$

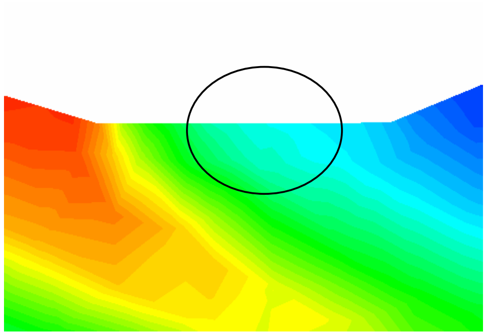

Fig. 10 Pressure distribution at Ma=7

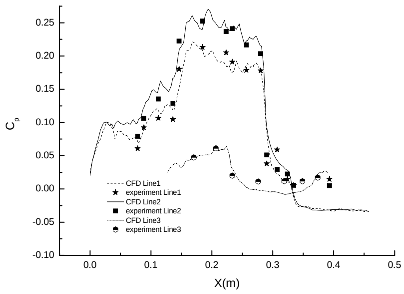

Fig. 11 $Ma = 5.993 \alpha = 4 \beta = 4$

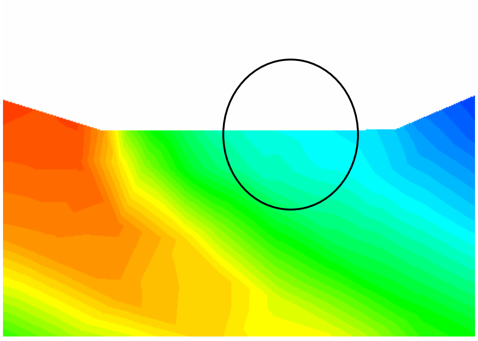

Fig.12 Pressure distribution at $Ma = 5.993\alpha = 4\beta = 4$

The comparison of experimental and computational results can be seen in Fig. 5 to Fig. 10 for pressure coefficient. In Ma=5, 6, 7, the LES show excellent agreement with the experimental results besides the afterbody. When comparing the results in afterbody the LES mode model low predicts the pressure coefficient significantly.

Comparing Fig. 9 to Fig. 5 and Fig. 7, we can see that LES model show excellent agreement in the condition of Ma=5 and Ma=6. In the point 5-9 at line 1, the LES model low predicts about 12.5% in Ma=7. The reason can be found by the pressure distribution. In the pressure distribution, the key regions are over dictated by a circle. From the picture, we can see that distribution are swirling in the condition of Ma=7. Maybe, the calculation errors are mainly conducted by the distribution swirling.

Comparing Fig. 11 to Fig. 5 to Fig. 9, we can see that the calculation wave appear in line 1 and line 2. Maybe in these conditions, the air flows are unsteady because of the sideslip and attach flight. The same wave distributions are also appearing in the Fig.12. In this section, the LES are successful in the prediction the pressure wave in hypersonic flow.

V. Conclusion

LES with mixed subgrid-scale model has been used to simulate aerodynamic performance of hypersonic configuration. The simulation was conducted to replicate conditions and geometry of a model which has been previously tested. LES Model has been successful in predict pressure coefficient with the max error 1.5% besides afterbody. But in the high Mach number condition, it is poor in predict ability and product 12.5% error. The calculation errors are mainly conducted by the distribution swirling. The fact of poor ability in the high Mach number and afterbody region indicated that the mixed subgrid-scale model should be improved in large eddied especially in hypersonic separate region. In the condition of attach and sideslip flight, the calculation results have waves. LES are successful in the prediction the pressure wave in hypersonic flow.

Acknowledgment

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