NUMERICAL STUDY OF AN OSCILLATORY TURBULENT FLOW OVER A FLAT PLATE*

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ABSTRACT: Oscillatory turbulent flow over a flat plate is studied using large eddy simulation (LES) and Reynolds-average Navier-Stokes (RANS) methods. A dynamic subgrid-scale model is employed in LES and Saffman's turbulence model is used in RANS. The flow behaviors are discussed for the accelerating and decelerating phases during the oscillating cycle. The friction force on the wall and its phase shift from laminar to turbulent regime are also investigated for different Reynolds numbers.

KEY WORDS: turbulent flow, large eddy simulation (LES), Reynolds-average Navier-Stokes (RANS), subgrid-scale (SGS) model, oscillatory flow

1 INTRODUCTION

Oscillatory turbulent flow over a flat plate has its theoretical and practical significance. This problem is relevant to the interaction between surface gravity waves and sea bottom and to the understanding of wave damping and sediment transport in shallow waters. As the waves propagate from the generating area towards the coast, usually the flow in the bottom layer develops from a laminar to a turbulent regime. On the other hand, the characteristics of such an oscillatory flow is quite different from wall turbulence which is steady in the mean. Therefore, an investigation of the oscillatory turbulent flow has its significance in the aspects of unsteady transition from laminar to turbulence, coherent turbulent structures, profiles of the mean velocity, and the shear stress on the wall for the accelerating and decelerating phases.

Although some experimental investigations have been done, such as Hino et al., little numerical simulation was performed for oscillatory turbulent flow over a wall. Blondeaux studied the turbulent boundary layer generated by an oscillating flat plate in a fluid at rest using the Reynolds-average Navier-Stokes (RANS) method based on the boundary layer approximation. It is well known that the large eddy simulation (LES) is developing to become one of the most powerful computational tools available for the calculation of turbulent flows. Lu et al. employed LES method to calculate oscillating flows past a circular cylinder, where the spectral method coupled with the finite-difference was used to solve the resolved Navier-Stokes equations.

Received 18 June 1998, revised 9 December 1998

* The project supported by the Youngster Funding of Academia Sinica and by the National Natural Science Foundation of China
In this study, an oscillatory turbulent flow over a flat plate is studied by using LES and RANS methods. In LES, the filtered time-dependent three-dimensional incompressible Navier-Stokes equations are solved using the non-staggered-grid, frictional step method as shown in Zang et al.\cite{4}, and a dynamic subgrid-scale model proposed by Germano et al.\cite{5} was employed. In RANS, Saffman’s turbulence model\cite{6} was used for the RANS simulation.

2 MATHEMATICAL FORMULATION

2.1 Formulation in LES

We used the filtered time-dependent three-dimensional incompressible Navier-Stokes equations. The governing equations are

\[ \frac{\partial u_i}{\partial x_j} = 0 \]  \hspace{1cm} (1)

\[ \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j} - \tau_{ij}\right) \] \hspace{1cm} (2)

where \( i, j = 1, 2, 3, \) \( u_i \) represents the Cartesian velocity components, \( p \) is the pressure divided by fluid density, \( \nu \) is the kinematic viscosity and \( \tau_{ij} \) represents the unresolved subgrid scale (SGS) stress term defined as

\[ \tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \] \hspace{1cm} (3)

This SGS quantities are modeled using the dynamic subgrid-scale eddy viscosity model in Germano et al.\cite{5}. The dynamic SGS eddy viscosity model is able to calculate the model coefficient using the resolved variables by filtering the governing equation at two different scales.

In the present study, we employ a stretching transformation along the wall-normal direction to increase the grid resolution near the wall, which is written as

\[ x_2 = D \left\{ \frac{1}{a} \tanh[(\xi_2 - 1) \tanh^{-1}(a)] + 1 \right\} \] \hspace{1cm} (4)

where \( D \) represents the domain size in the wall-normal direction and \( a \) is a stretching constant. Further we use the maximum velocity \( U \) and the amplitude \( A \) of the oscillatory flow as the velocity and length scales respectively, then Eqs.(1) and (2) are transformed into curvilinear coordinates in nondimensional conservation form,

\[ \frac{\partial U_m}{\partial \xi_m} = 0 \] \hspace{1cm} (5)

\[ \frac{\partial J^{-1} u_i}{\partial t} + \frac{\partial F_{im}}{\partial \xi_m} = 0 \] \hspace{1cm} (6)

and the flux \( F_{im} \) is

\[ F_{im} = U_m u_i + J^{-1} \frac{\partial \xi_m}{\partial x_i} p - \left( \frac{1}{Re} + \frac{1}{Re_r} \right) G^{mn} \frac{\partial u_i}{\partial \xi_n} \] \hspace{1cm} (7)

where \( m, n = 1, 2, 3, \) \( Re \) is the Reynolds number and \( Re_r \) represents the Reynolds number based on turbulent viscosity calculated by the dynamic subgrid-scale eddy viscosity model\cite{5}.