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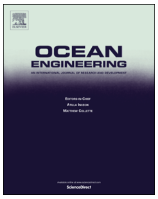

Detached eddy simulation of turbulent flow around square and circular cylinders on Cartesian cut cells

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ABSTRACT

Square and circular cylinders in three-dimensional turbulent flows are studied numerically using the LES and DES turbulence models. One aim of the present study is to implement the LES and DES turbulence models in a cell-centered finite volume method (FVM) developed for solving the Navier–Stokes equations on Cartesian cut cells. The Cartesian cut cell approach is known to be robust for problems in geometrically complex domains with fixed or moving boundaries. For the purpose of validating the present numerical model, the current flow past fixed square and circular cylinders at moderate Reynolds numbers is tested first. Comparison of the computed results with experimental data reveals that the DES models are superior to the conventional LES and RANS models. The second aim of the present study is to assess the performance of different RANS based DES turbulence models. By means of the comparison of results obtained with the 0-equation mixing-length, 1-equation S–A and 2-equation k–ω based DES models for the flow over the same circular cylinder, some recommendations are proposed. According to the present study, in terms of accuracy the 1-equation S–A based DES model is very promising. Beside this, if the computational cost is the main concern, the 0-equation mixing-length based DES model might be an ideal option, achieving a good balance between accuracy and efficiency.

1. Introduction

Most flows of significant engineering relevance are turbulent flows dominated by large-scale unsteadiness and coherent vortex shedding. To successfully simulate such kinds of flows is a big challenge, especially when the computational domain is complex or a moving boundary is considered. Due to the dramatic progress in computer technology, computational fluid dynamics (CFD) is now able to handle such industrially relevant flows at moderate costs. At the present time, there have been several different computational approaches for simulating turbulent flows. The most accurate approach to turbulence simulation is to solve the Navier–Stokes equations directly, without averaging or approximation (Evangelinos et al., 2000; Ma et al., 2000; Tremblay et al., 2000; Archer et al., 2008). This direct numerical simulation (DNS), in principle, is the only method capable of capturing all aspects of turbulence. However, the direct resolution of the turbulent motion is infeasible, as the associated grid resolution would cause prohibitive computational expenses. Therefore, most of the current DNS applications are aimed at the simulation of flows at low Reynolds numbers. In the foreseeable future, it is likely that computers will not be able to meet the challenge of a high Reynolds number calculation using the method of DNS.

In the past, the Reynolds-averaged Navier–Stokes equations (RANS) seemed to be the only option to calculate turbulent flows of industrial interest (Liang and Cheng, 2005; Wanderley et al., 2008). In the framework of RANS, all aspects of turbulence are modeled, which enhances the numerical efficiency at the expense of a strong model dependency. Generally speaking, RANS models work well in flows in which slow varying coherent structures contribute a considerable portion of the total turbulence kinetic energy (Spalart, 2000). Due to the fact that a statistical or temporal average is being adopted, RANS calculations often fail to capture unsteady flow phenomena in the wake behind bluff bodies or airfoils at high angles of attack. On the other hand, large eddy simulation (LES) of turbulent flows is thought to be the most accurate method for high Reynolds numbers which exceed the present DNS capability. LES is much less sensitive to modeling errors since only the small subgrid scales of motion are modeled. However, LES demands very fine near-wall resolution to directly resolve the turbulent structures. This is basically due to the absence of universal wall functions, which would allow for a reduced number of grid points in the near-wall region (Schmidt and Thiele, 2002). For this reason, wall-resolving LES remains

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fairly time consuming, disqualifying this method for industrial applications especially at higher Reynolds numbers. Some successful results with LES have been reported by Kitagawa and Ohta (2008) and Liang and Papadakis (2007) on one or two stationary circular cylinders in a cross-flow.

Recently, the detached eddy simulation (DES) has become a promising tool for the prediction of turbulence as it offers a reduced computational effort in comparison to LES while retaining much of the physical accuracy of the method. The DES was first proposed by Spalart et al. (1997) in 1997 based on the Spalart–Allmaras (S–A) eddy-viscosity RANS model (Spalart and Allmaras, 1994). This was followed by a more general discussion in Travin et al. (2000). The DES method aims to combine the fine-tuned RANS methodology in the attached boundary layers with the power of LES in the shear layers and separated flow regions, thereby considerably reducing the cost of the computations. Unlike other hybrid models which explicitly divide the solution domain into distinct RANS and LES regions with matching of the two different models being an issue, the DES method provides a seamless transition between the two regions by adopting a single turbulence model. To date, there have been a number of successful DES applications ranging from classical configurations such as the flow over a cylinder and sphere to complex geometries including fighter aircraft (Spalart, 2000; Bunge et al., 2007; Hasama et al., 2008; Squires et al., 2008).

From the above discussion, it may be observed that the DES is constructed on the basis of a certain RANS turbulence model. However, different types of RANS models are available currently. In short, we can classify them into 0-equation model, 1-equation model and 2-equation model, according to the number of additional transport equations to be solved in the RANS models. In this paper, the different RANS based DES turbulence models will be evaluated, using the example of flow over a circular cylinder. Although detailed comparisons of the different turbulence models have been reported in the past, such as the comparison of LES, RANS and DES models for flows past cubes and spheres (Iaccarino et al., 2003) or a flat plate (Breuer et al., 2003), similar comparisons between different RANS based DES models have, to the best of the authors' knowledge, yet appeared in the literature for any flow problem. In the following, the 0-equation RANS model refers to the mixing-length turbulence model, and the 1-equation and 2-equation models are chosen as the widely used S–A and k–ω turbulence models respectively.

The aims of the present paper are twofold. The first is to implement the different turbulence models in a numerical Navier–Stokes solver based on the Cartesian cut cell approach. This approach is an effective alternative to traditional structured and unstructured grids. Solid regions are simply cut out of a stationary background Cartesian mesh, and their boundaries are represented by different types of cut cells. Therefore, a single Cartesian mesh is composed of solid cells, fluid cells and partially cut cells. The cut cell mesh generation is relatively straightforward through calculations for the boundary segment intersections with the background Cartesian mesh. Furthermore, moving boundaries can be easily accommodated by re-computing cell-boundary intersections, rather than re-meshing the whole flow domain or large portions of it. For this reason, the Cartesian cut cell approach is very suitable for complex computational domains or moving boundaries that exist in a broad class of engineering problems. This method has recently been applied successfully to the shallow water equations (Causon et al., 2001; Liang et al., 2007), and extended to deal with incompressible viscous flows (Chung, 2006; Bai et al., 2010). In the present paper, the different turbulence models, including the Smagorinsky-type LES model, the 0-equation, 1-equation and 2-equation RANS models and the corresponding DES models are incorporated into this robust Navier–Stokes solver. The developed numerical model is verified by comparisons with experimental data for flow over square and circular cylinders. The validation indicates the effectiveness of the DES turbulence model, when it is even constructed on the basis of the simplest 0-equation RANS model.

The second aim is to carry out the aforementioned comparison between the different RANS based DES models. Through the comprehensive comparison of the mean velocity and Reynolds stress components in the wake behind the circular cylinder, particular DES turbulence models are identified as the better options for this case, in terms of accuracy and efficiency.

2. Mathematical formulation

The conventional numerical approaches to turbulent flows are the RANS and the LES methods, both of which need to solve the averaged Navier–Stokes equations. However, the average is taken over a certain time period in RANS, while it is a spatial average over a small volume in LES. Due to the nonlinearity of the Navier–Stokes equations, models are needed in order to close the averaged equations, which are termed turbulence models in RANS and subgrid scale models in LES.

2.1. Smagorinsky LES turbulence model

In the LES method, a space filter function is used to filter the continuity and Navier–Stokes equations. The filtered governing equations then read

$$\frac{\partial \overline{u}_j}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t}+\overline{u}_j\frac{\partial \overline{u}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i}+\nu\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j}-\frac{\partial}{\partial x_j}\left(\overline{u_i u_j}-\overline{u}_i\overline{u}_j\right)+g_i \tag{2}$$

where the overbar denotes the filtered (resolvable) quantities, u_i is the filtered velocity, ρ and ν are the density and the kinematic viscosity of the fluid, g is the acceleration due to gravity and p denotes the pressure. The new term appearing in the filtered equations is:

$$\tau_{ij}=-\left(\overline{u_i u_j}-\overline{u}_i\overline{u}_j\right) \tag{3}$$

where τ_{ij} is called the subgrid scale (SGS) Reynolds stress. It is noticed that τ_{ij} is similar to the RANS Reynolds stress, but the physics it represents is different. In RANS models, all the turbulent motions are modeled, while in LES models, only the turbulent motions smaller than the filter size (subgrid scale) are modeled and the motions larger than the filter size (large eddies) are explicitly computed. The large scale motions are affected by the flow geometry and are different from flow to flow, but the small scale motions are more universal. Therefore, it is reasonable to expect that the model closure for LES models is less demanding than that for RANS models, and LES models are more accurate and reliable than RANS models especially for flows in which large-scale unsteadiness is significant.

Using the Boussinesq assumption, we obtain the final form of the space filtered Navier–Stokes equations,

$$\frac{\partial \overline{u}_i}{\partial t}+\overline{u}_j\frac{\partial \overline{u}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\nu+\nu_T)\frac{\partial \overline{u}_i}{\partial x_j}\right]+g_i \tag{4}$$

where ν_T is the SGS eddy viscosity. Now, we need a turbulence closure to model the unresolved scale (SGS) motions. The most basic subgrid scale model is the one proposed by Smagorinsky in 1963, which is called the standard Smagorinsky model. In this turbulence model, the form of the subgrid scale eddy viscosity can