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Comparative assessment of PANS and DES for simulation of flow past a circular cylinder

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ABSTRACT

Flow past a circular cylinder at two subcritical Reynolds numbers ($Re = 3900$ and $Re = 1.4 \times 10^5$) is simulated by partially-averaged Navier–Stokes (PANS) method and detached eddy simulation (DES). *The objective of current study* is to evaluate the properties of PANS models in the simulation of unsteady turbulent flows. The model performance is assessed by a detailed comparison of PANS predictions to the corresponding experimental data and DES results. The computed pressure distribution, velocity profiles along with Reynolds stresses are presented in the comparison. The control parameter relevant to PANS models which determines the ratio of unresolved-to-total kinetic energy (f_k) is adopted as either a constant or a spatially varying function. As expected, fine-scale vortical structures are resolved at a low value of f_k. The numerical results from PANS show its comparable capabilities with DES for simulation of massively separated flows and its potential application in the prediction of industrial turbulent flows.

1. Introduction

Turbulent flows past bluff bodies involve very complex phenomena such as separation, reattachment and vortex shedding. Such flows are commonly observed in many applications. Although Reynolds-averaged Navier–Stokes (RANS) models have been applied successfully in many practical computations and appear to yield accurate predictions in attached flows as well as some with shallow separations, they tend to fail for massively separated flows. Direct numerical simulation (DNS) resolves all scales of turbulent motions avoiding the limitations associated with turbulence modeling, whereas it is computationally impractical for DNS to handle industry turbulent flows. Large eddy simulation (LES), which directly calculates the large turbulent scales dependent on geometry with the fine scale turbulence modeled, attempts to reduce the grid requirements of DNS. However, it remains too expensive for LES to be widely used in practical applications due to the excessive computing power requirements in high-Reynolds number boundary layers. In order to resolve the small but dynamically important eddies in the near-wall region, the required number of grid points for LES is nearly the same as for DNS (Catalano et al., 2003). Hybrid RANS/LES methods have been proposed in recent years, which combine the advantages of RANS and LES aiming at computing unsteady turbulent flows at an affordable computational expense, for a review, see Fröhlich and von Terzi (2008).

Detached eddy simulation (DES), as a typical hybrid method firstly proposed by Spalart et al. (1997), is designed to treat the entire boundary layer with RANS and apply an LES treatment in the regions away from solid surfaces. Partially-averaged Navier–Stokes (PANS) method as another bridging approach originally introduced by Girimaji et al. (2003) enables a seamless transition from RANS to DNS depending on f_k (the ratio of unresolved-to-total kinetic energy) and f_ε (the ratio of unresolved-to-total dissipation) within the flow domain. Both of the two hybrid methods are adopted in present contribution for simulation of a circular cylinder in a cross flow.

Flow past a circular cylinder is a classical example of bluff body flows. The complex flow structures and rich physics have been both experimentally and numerically investigated for the past few decades. As well known, the circular cylinder flows exhibit vastly different features as the Reynolds number (Re), for a review of the flow over cylinders, see Williamson (1996). In this paper, we focus on the flows at two subcritical Reynolds numbers ($Re = 3900$ and $Re = 140{,}000$). For the flow in subcritical state, the boundary layer on circular cylinder remains laminar while the separated shear layer becomes unstable and later rolls up into turbulent eddies.

The majority of numerical studies have been performed for $Re = 3900$ (based on cylinder diameter and freestream velocity) mainly due to the availability of well documented experimental data and the accessibility of highly resolved large eddy simulation. Norberg (1987) presented measurements on surface pressure and

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shedding frequency for a range of Reynolds numbers. Lourenco and Shih (1993) measured mean velocity profiles as well as Reynolds stresses in the near wake at $Re=3900$ using particle image velocimetry (PIV). Ong and Wallace (1996) provided measurements of mean flow data in the near wake of a cylinder at the same Reynolds number. Beaudan and Moin (1994) were the first to conduct a comprehensive LES study on the cylinder flow at $Re=3900$. They simulated the subcritical flow using high order upwind-biased schemes based on a compressible solver. The profiles of mean velocity and Reynolds stresses from Beaudan and Moin (1994) showed reasonable agreement with the experimental data. Breuer (1998) carried out an LES investigation of the flow past a circular cylinder at $Re=3900$ with emphasis on numerical and modeling aspects related to LES. The investigation confirmed that central schemes were better suited for LES than upwind schemes. Kravchenko and Moin (2000) employed LES based on B-splines to perform a detailed comparison of numerical results with the existing experimental data. Their numerical results agreed well with the experimental data from Norberg (1987), Lourenco and Shih (1993) and Ong and Wallace (1996).

Cantwell and Coles (1983) provided extensive measurements in the near wake of a circular cylinder at a high Reynolds number ($Re=140{,}000$). Roshko (1961) conducted experimental studies of the cylinder flow at $Re=10^6$–10^7 with emphasis on the variation of separation, drag coefficient and Strouhal number with the Reynolds number. Numerical studies of flow over a circular cylinder at high Reynolds numbers are comparatively rare. Travin et al. (1999) performed numerical studies of flow past a circular cylinder at $Re=140{,}000$ using DES method. Both laminar and turbulent separation results were obtained and compared with the experimental data of Cantwell and Coles (1983) and Roshko (1961). Breuer (2000) made a thorough numerical investigation of circular cylinder flow at $Re=140{,}000$ using LES with a focus on the performance of subgrid scale model. The LES results (Breuer, 2000) from dynamic model were generally satisfactory when compared with the experimental data of Cantwell and Coles (1983). Kim (2006) carried out an LES investigation of flow around a circular cylinder at several subcritical Reynolds numbers. The obtained results from commercial software were in good agreement with the corresponding experimental data.

PANS models as recently proposed hybrid strategies were applied to the simulations of cylinder flows in the past few years. PANS method based on k–ε formulation was used by Lakshmipathy and Girimaji (2010) for the simulation of flow past a circular cylinder at $Re=140{,}000$. Their PANS simulations were performed with three constant f_k values ranging from 0.5 to 0.7. k–ε PANS computations were also performed by Lakshmipathy et al. (2011) for a low Reynolds number case ($Re=3900$). Although significant improvements over RANS were shown in their PANS simulations, the accuracy of predictions was difficult to say satisfactory when compared with the LES results. Lakshmipathy and Togiti (2011) performed DES and two PANS computations for the cylinder flow at $Re=140{,}000$. Both DES and PANS equations were derived from Menter SST turbulence model (Menter, 1994). Their numerical results were compared with the experimental data (Cantwell and Coles, 1983) and Breuer's LES results (Breuer, 2000) but showed considerable discrepancies with under-predicted drag coefficient in all calculations. Most PANS simulations of flow past a circular cylinder were performed using constant f_k values throughout the whole domain. The smallest f_k was chosen as 0.5 mostly and gave the best results despite of considerable deviations from the experiments. In addition, comparisons of higher order moments were not carried out in previous PANS computations. Spatially varying f_k PANS based on k–ε formulation was adopted by Abdol-Hamid and Girimaji (2004) and Elmiligui et al. (2004) for the simulation of cylinder flow at $Re=50000$, however, no detailed comparisons with the existing measurements were conducted.

In present work, PANS simulations of flow past a circular cylinder at two subcritical Reynolds numbers have been performed using both constant and spatially varying f_k values. DES calculations are also conducted for comparisons. The main objective of current work is not to study the physics of circular cylinder flow but to assess the capability of PANS approach in prediction of unsteady turbulent flows and to carry out a detailed comparison of numerical results with the available experimental data.

2. Modeling strategies

2.1. Detached eddy simulation

The majority of DES formulations to date are derived from the Spalart–Allmaras one-equation model (Spalart and Allmaras, 1994). Strelets (2001) presented an analogous formulation based on the Menter SST two-equation model (Menter, 1994). Wilcox's k–ω model behaves well in the near wall region and has proven accurate for boundary layers in adverse pressure gradients but deserves a severe sensitivity to the freestream values of ω (Menter, 1992). On the other hand, the standard k–ε model behaves relatively insensitive to the freestream values but is incapable of accurately predicting flow separation. Menter's SST model reduces to a k–ω model near solid walls while shifts to a k–ε model away from solid surfaces. The model combines the best features of k–ω and k–ε and is widely used for the prediction of aeronautics flows. In present work, we use the two-equation SST DES model of Strelets (2001) and the model transport equations are given as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho U_i k)}{\partial x_i}=\tilde{P}_k-\beta^*\rho k\omega\times F_{\rm DES}+\frac{\partial}{\partial x_i}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_i}\right] \tag{1}$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho U_i\omega)}{\partial x_i}=\frac{\gamma}{\nu_t}\tilde{P}_k-\beta\rho k\omega^2+\frac{\partial}{\partial x_i}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_i}\right]+2(1-F_1)\frac{\rho\sigma_{\omega2}}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial\omega}{\partial x_i} \tag{2}$$

where, k is the turbulence kinetic energy, ω is the specific dissipation rate, ρ is the density, μ is the dynamic viscosity and U_i is the flow velocity.

The blending function F_1 is defined by:

$$F_1=\tanh\left\{\left\{\min\left[\max\left(\frac{\sqrt{k}}{\beta^*\omega d},\frac{500\mu}{d^2\rho\omega}\right),\frac{4\rho\sigma_{\omega2}k}{CD_{k\omega}d^2}\right]\right\}^4\right\} \tag{3}$$

with $CD_{k\omega}=\max\left((2\rho\sigma_{\omega2}/\omega)(\partial k/\partial x_i)(\partial\omega/\partial x_i),10^{-10}\right)$ and d is the distance to the nearest wall.

The turbulent eddy viscosity is obtained from

$$\mu_t=\min\left(\frac{\rho k}{\omega},\frac{\rho a_1 k}{SF_2}\right) \tag{4}$$

where S is the invariant measure of the strain rate, $a_1=0.31$ and F_2 is a second blending function defined as

$$F_2=\tanh\left\{\left[\max\left(\frac{2\sqrt{k}}{\beta^*\omega d},\frac{500\mu}{d^2\rho\omega}\right)\right]^2\right\} \tag{5}$$

The production term is expressed as

$$P_k=\mu_t\frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right);\quad \tilde{P}_k=\min(P_k,10\times\beta^*\rho k\omega) \tag{6}$$

All constants are calculated by a blend via $\alpha=F_1\alpha_1+(1-F_1)\alpha_2$. This model constants are: $\beta^*=0.09$, $\gamma_1=5/9$, $\gamma_2=0.44$, $\beta_1=0.075$, $\beta_2=0.0828$, $\sigma_{k1}=0.85$, $\sigma_{k2}=1.0$, $\sigma_{\omega1}=0.5$, $\sigma_{\omega2}=0.0828$. $F_{\rm DES}$ in