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Large-eddy simulation of the flow normal to a flat plate including corner effects at a high Reynolds number

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ABSTRACT

Numerical investigations of the flow normal to a flat plate with the thickness ratio (thickness/height) of 0.02 have been carried out using three-dimensional large-eddy simulations (LESs). The Reynolds number (Re) based on the height of the plate (H) is 1.5×10^5. The plate corners are rounded with the curvatures of two different radii, i.e. $r=0.01H$ and $0.005H$. A low-frequency unsteadiness is indicated in the flow patterns and the flow switches alternately between the high and low drag regimes. This flow regime switch is more frequent in the sharp corner case ($r=0.005H$) than that in the smooth corner case ($r=0.01H$). The sharp corners complicate the flow pattern, increase the mean drag and the fluctuations of drag and lift forces on the plate, as well as the kinetic energy in the near wake. The instantaneous drag force is found to be reversely related to the instantaneous spanwise averaged recirculation length. The pressure and friction force components, Reynolds-averaged statistics distributions and the turbulent wake structures are also presented and discussed systematically.

1. Introduction

A uniform incoming flow past a normal flat plate is one of the classical problems in fluid mechanics. This idealized bluff body flow which is of great interest for a wide range of engineering applications, such as hydrodynamic loading on ship stabilizers and heave damping plates in truss spar platforms. Many of these engineering applications are often subject to high Reynolds number flows.

Several experimental studies have been performed for the flow past a flat plate. Most of them (Fage and Johansen, 1927; Kiya and Matsumura, 1988; Leder, 1991; Lisoski, 1993; Mazharglu and Hacısevki, 1999; Amandolese et al., 2013) were carried out at high Reynolds numbers ($\mathrm{Re}=U_\infty H/\nu$, where U_∞ is the free stream velocity, H is the height of the plate and ν is the kinematic viscosity of the fluid), i.e. $\mathrm{Re}\gtrsim10^3$. The only exception is the measurements conducted by Dennis et al. (1993) for $5\le\mathrm{Re}\le20$, where the flow was found to remain symmetrical and stable. One of the earliest experiments was for the flow around a sharp-edged plate with various flow incidence angles at $\mathrm{Re}=1.5\times10^5$ by Fage and Johansen (1927). The pressure distribution over the surface of the plate was measured with a Chattock tilting gauge, and the pressure on the back side of the plate was reported to be constant for the flow normal to the plate. Moreover, at some specific points in the wake region, the speed was also measured by the hot wire technique and analyzed in detail. In the last two decades, the velocity and Reynolds stress distributions for the flow normal to the

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plate were measured in wind tunnels and discussed systematically (see e.g. Kiya and Matsumura, 1988, $\mathrm{Re}=2.3\times10^4$; Leder, 1991, $\mathrm{Re}=2.8\times10^4$; Mazharglu and Hacısevki, 1999, $\mathrm{Re}=3.3\times10^4$). The existence of saddle points in the flow field was demonstrated, and the locations of the extremum values for the Reynolds stresses were reported to occur upstream of the saddle points (Leder, 1991). Lisoski (1993) investigated the wake structures for a high attack angle (87.5–90°) plate at $\mathrm{Re}=1\times10^3$–1.25×10^4 using laser-induced fluorescence (LIF) in a towing tank.

Numerous theoretical and numerical studies of the flow over a flat plate have been performed. In the early studies, the flow was assumed to be two-dimensional (2-D). Tamada and Miyagi (1962) solved the 2-D Navier–Stokes (NS) equations mathematically based on Oseen's approximation. A formula for the drag force coefficient was derived as $C_D\sim\pi+8\Gamma(3/4)\mathrm{Re}^{-3/4}$ (Γ is the gamma function) for $\mathrm{Re}>0$. By comparing their work with the experimental results, e.g. Fage and Johansen (1927), it appears that their formula fails for large Re. Hudson and Dennis (1985) calculated the flow normal to a plate at $0.1\le\mathrm{Re}\le20$. The flow was assumed to be 2-D, viscous and incompressible. Dennis et al. (1993) extended the work of Hudson and Dennis (1985) and carried out the numerical simulations for Re up to 100. Tamaddon-Jahromi et al. (1994) carried out 2-D simulations using a Taylor–Galerkin/pressure-correction finite element algorithm for $\mathrm{Re}=126$, 250 and 500. The Strouhal numbers ($\mathrm{St}=fH/U_\infty$, where f is the vortex shedding frequency) calculated in their simulations agreed well with the experimental results by Taneda and Honji (1971). In et al. (1995) investigated numerically the flow at various incidence angles to a flat plate for $0.1\le\mathrm{Re}\le30$. A new method was developed to treat the singularity at the tips of the plate analytically. Lasher (2001) simulated the 2-D blocked flow normal to a flat plate at $\mathrm{Re}=32\,200$ using four different versions of the k–ε turbulence model. The trend of the drag force varying with the blockage ratio was successfully predicted by comparing with the experimental results by Takeuchi and Okamoto (1983). However, the drag force was not correctly calculated. Recently, Najjar and Vanka (1995b) carried out 2-D direct numerical simulations (DNSs) for the flow normal to a flat plate at $80\le\mathrm{Re}\le1000$. The mean drag force was overpredicted by a factor of 1.6 compared with the experimental results by Fage and Johansen (1927). Lisoski (1993) reported a similar overprediction of the drag force based on his experiments and 2-D numerical simulations. Tian et al. (2013) calculated the flow normal to flat plates with different thickness ratios ($R=t/H=$ 0.05–1, where t is the thickness of the plate) by 2-D simulations. They pointed out that three-dimensional (3-D) simulations should be adopted for the plates when $R<0.6$. The first 3-D numerical simulation was carried out by Najjar and Vanka (1995a). They compared 2-D and 3-D DNS results for a flat plate at $\mathrm{Re}=1000$, and large discrepancies between 2-D and 3-D results for the drag coefficients and the vortex formation were reported. However, the drag coefficients in the 3-D simulations agreed well with the experimental results. A low-frequency behavior, i.e. the flow gradually varies between two different regimes: regime H (high drag) and regime L (low drag), was discussed systematically through a 3-D DNS for the flow normal to a flat plate at $\mathrm{Re}=250$ by Najjar and Balachandar (1998). Narasimhamurthy and Andersson (2009) calculated the turbulent wake behind a normal flat plate for $\mathrm{Re}=750$ using the DNS method. Wake patterns, vortex structures, time-averaged pressure, velocity and Reynolds-stress distributions were presented in their paper. More recently, some numerical studies about the fluid dynamics around a flat plate have also been carried out, see e.g. Huang et al. (2014) and Hargreaves et al. (2014).

The drag force on a normal flat plate is significantly overestimated in 2-D simulations. However, accurate predictions of the drag force are of great importance in engineering applications. For example, heave damping plates are installed on Spar oil drilling and production platforms in order to increase the added mass of the platform and make sure that the natural frequency in heave motion is below and outside the wave frequency range. If the force on the heave plates is overestimated, the natural heave motion frequency of a Spar buoy will be underestimated accordingly. Thus, the real natural heave motion frequency at sea may increase and approach the wave frequency range, and thus resulting in a large heave response. Consequently this may lead to serious damages in the drill pipes, risers, anchor chains and onboard equipment. To the authors' knowledge, all the 3-D numerical simulations were carried out at low Reynolds numbers, i.e. $\mathrm{Re}\lesssim10^3$. However, for most real case applications, e.g. offshore structures at sea and vehicles in the air, the Reynolds number can easily reach high values, e.g. $\mathrm{Re}=10^5$–10^8. Thus, 3-D numerical simulations of flow around a flat plate at high Reynolds numbers are required.

In this study, the 3-D flow past a normal flat plate with R=0.02 at $\mathrm{Re}=1.5\times10^5$ is investigated using a large-eddy simulation (LES) method. The choice of this Reynolds number is based on the possibility of comparing the results with the experiments carried out by Fage and Johansen (1927) at the same Reynolds number. It should be noted that the cross-sectional shapes of the plates are not constant in the previous studies: thin rectangles (see e.g. Fromm and Harlow, 1963; Mazharglu and Hacısevki, 1999; Narasimhamurthy and Andersson, 2009; Tian et al., 2013), tapered sharp-edged plates (see e.g. Fage and Johansen, 1927; Hudson and Dennis, 1985; Kiya and Matsumura, 1988; Leder, 1991; Dennis et al., 1993; Lisoski, 1993; Tamaddon-Jahromi et al., 1994; Lasher, 2001) and zero-thickness plates (see e.g. Tamada and Miyagi, 1962; In et al., 1995; Najjar and Vanka, 1995a, 1995b; Najjar and Balachandar, 1998). In order to resolve the detailed flow structures around the sharp edges of the plate tips, high grid resolution is required. However, this is not feasible due to the high Re simulations in the present study. Therefore, the corners are rounded in order to avoid the sharp edges. Similar treatment of the corners of a square cylinder has been employed in Zheng and Dalton (1999). Previous studies (Tao and Thiagarajan, 2003; Tao et al., 2007) demonstrated that the corner radius of the oscillating plates has influences on the vortex shedding pattern and the force coefficients of the plates. In order to study the effects of rounded curved edges on the flow field, the results of two different curvatures will be compared and discussed in the present study.

The outline of the remainder of the paper is as follows. The mathematical formulation and numerical methods are given in Section 2. The computational overview, convergence and validation studies are presented in Section 3. The results and discussion are described in Section 4. Finally, the concluding remarks are given in Section 5.

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