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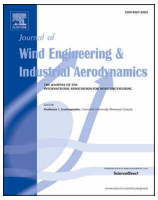

On simulating the flow past a normal thin flat plate

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ABSTRACT

Initially, the uniform flow past a normal two-dimensional flat plate of zero-thickness was studied using Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) at Reynolds number of 1200. An extensive review of previous numerical and experimental studies on the wake of flat plates highlights important discrepancies, which are reconciled by the present detailed sensitivity study of domain, boundary conditions and turbulence modeling specifications. It is shown that differences in important flow features, such as the mean recirculation length, drag and pressure distributions are related to the strong $Re-$effects for $Re < 1000$. Detailed comparison of DNS and LES studies at $Re = 1200$ with measurements up to $Re = 1.5 \times 10^5$ suggest that for $Re > 1000$, the influence of the Reynolds number is small. Moreover, it is found that some important differences in the LES and DNS simulations, despite similar grid resolution, can be related to specific behavior of the Sub-Grid Scale Smagorinsky model in regions of high anisotropy and adverse pressure gradient in the recirculation zone even at high Re. Finally, it is observed that the pressure distribution on the windward surface of the plate is highly sensitive to the wake flow, which helps explain discrepancies between experimental and numerical studies in terms of an unusual sensitivity to the experimental conditions.

1. Introduction

Bluff-body flows, such as flow past bridges, free-standing structures and buildings, are important in the areas of civil and wind engineering, structural design and fluid-solid interactions. These flows are generally characterized by quasi-periodic three-dimensional turbulent wakes. Many studies have focused on understanding wake structures in bluff body flows. However, despite the simple geometry of a flat plate, which makes it a reference geometry, there has been limited investigations of its wake over the years compared to the extensive study of the wake of cylinders (Roshko, 1961; Bearman, 1968; Kiya et al., 1982; Niemann and Holscher, 1990; Okamoto and Sunabashiri, 1992; Lyn et al., 1995; Williamson, 1996a; Bailey et al., 2002; Wang et al., 2009).

Most experimental studies on the wake of infinite span normal thin flat plates are restricted to high Reynolds numbers of $Re = U_0 h/\nu = 10^4 - 10^5$; where U_0 is the free stream velocity, h is the plate chord and ν is the kinematic viscosity of the fluid: Fage and Johansen (1927); Roshko (1954); Fail et al. (1959); Kiya et al. (1982); Leder (1991); Wu et al. (2005). Fage and Johansen (1927) measured the mean pressure distributions on a beveled sharp-edge plate and the vortex shedding frequency for several angles of attack at $Re = 1.5 \times 10^5$. The drag coefficient for the normal plate was estimated as 2.13 using surface pressure measurements, and the vortex shedding Strouhal number (defined as $St = f_s h/U_0$, where f_s is the shedding frequency) was estimated to be 0.146 using hot wire anemometry at different locations in the wake. Roshko (1954) studied the changes of vortex shedding frequency in the wake of an infinite span thin flat plate in comparison to those of low aspect-ratio (defined as chord-to-width ratio) plates, circular cylinders and other bodies to investigate the idea of "Universal Strouhal number". Fail et al. (1959) focused on the influence of aspect ratio on the flow characteristics (i.e., mean drag, mean pressure distribution and Strouhal numbers) in the wake of flat plates for a range of aspect ratios from 1.0 to 20 as well as infinite span. The studies by Roshko (1954) and Fail et al. (1959) suggested that the shedding frequency and drag coefficient are significantly affected by the presence of an after-body and that the two-dimensional (2D) limit was only approached for the largest aspect ratios. Kiya and Matsumura (1988) reported the first study of the wake structures formed behind normal beveled sharp-edge flat plates at $Re = 2.3 \times 10^4$ using hot wire anemometers. The profiles of phase-averaged velocities and Reynolds stresses showed that the contributions of velocity fluctuations at half the shedding frequency dominated the shear stresses. However, the error of these hotwire

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measurements is expected to be significant at the high turbulence levels observed in the wake (see, for example, Bradbury (1976)), which may explain the discrepancies observed when compared to the study of Leder (1991). Using Laser-Doppler-Velocimetry (LDV), Leder (1991) demonstrated the existence of saddle points in the wake (phased-averaged field) downstream of the locations of the maximum Reynolds stress values (maximum phased-average stress, e.g., $\langle v^2 \rangle_{max}$). Most recently, Wu et al. (2005) carried out smoke visualizations of the wake and hotwire measurements to qualitatively confirm the existence of two vortex formation lengths (S for short and L for long) in the wake of a normal sharp-edge (beveled) flat plate corresponding to the different vortex shedding regimes previously identified by the DNS study of Najjar and Balachandar (1998). Despite these studies, however, there has been no comprehensive and quantitative study of the wake structures and interactions for the flow past normal thin flat plates at moderate Reynolds numbers, which is the focus of numerical simulations ($Re = 30 - 1000$).

Most numerical studies of the flow past normal thin flat plates were restricted to low Re ($20 - 750$) with a number of Direct Numerical Simulations (DNS) at $Re = 1000$ (Najjar, 1994; Najjar and Balachandar, 1998) and one Large Eddy Simulation (LES) at $Re = 1.5 \times 10^5$ (Tian et al., 2014). The list of all studies on thin normal flat plates (including thin, zero-thickness, and sharp-edge plates) is identified by the authors in Table 1 along with the main differences amongst the simulations. Early 2D simulations (Tamaddon-Jahromi et al., 1994; Najjar and Vanka, 1995b) proved unsatisfactory in capturing the main characteristics of the wake. Amongst the different studies, a consensus has developed for the size of the computational domain that is necessary to obtain representative results: $15h - 25h$ between the plate and outlet boundary, $5h - 8h$ between top/bottom boundaries and the plate, and $4h - 2\pi h$ between the side-boundaries (spanwise width of the flat plate). These dimensions also agree with the later recommendation of Rodi et al. (1997) for the flow past cylinders. The majority of numerical studies on this topic have similar boundary conditions with the exception of the outlet boundary condition, which differed between the Neumann outflow (Narasimhamurthy and Andersson, 2009; Afgan et al., 2013; Tian et al., 2014) and Convective outflow (Najjar and Vanka, 1995b; Najjar and Balachandar, 1998) conditions. The other important difference between these studies is the number of spatial grid elements, which ranges between $10^6 - 10^7$ elements with no reported information on resolution of the Kolmogorov scales except for Narasimhamurthy and Andersson (2009). The coarser mesh corresponded to studies of flat plates with zero-thickness, while those with finer mesh focused on thin ($0.02h - 0.1h$) plates.

There is no consensus on some of the more important wake properties reported in the literature. Important differences in mean recirculation length, mean drag and vortex shedding frequency are shown in Table 1 for a range of Re from 250 to 1.5×10^5. These results suggest that simulating this wake is remarkably challenging despite the simple geometry of a flat plate. The complex wake structures and vortex dynamics reported by Najjar and Balachandar (1998) and Wu et al. (2005) may be responsible for the difficulties associated with simulating this wake. In the current study, the differences between numerical and experimental studies are explored to determine the reason for their discrepancies. The differences amongst numerical studies include boundary conditions and other computational characteristics, implications of which are examined in this study.

This paper aims to identify whether the discrepancies on the prediction of the wake of infinitely span thin flat plates normal to the uniform flow can be attributed to the differences on computational setup (e.g., grid resolution, and boundary domain), the flow Re, or the turbulence modeling technique. To this end, a sensitivity analysis is conducted on boundary conditions, domain size (not explored in detail) and grid quality. Moreover, it examines the vortex shedding dynamics using DNS and LES (Dynamic Smagorinsky-Lilly Model). The results from the DNS and LES are compared with the available results in the literature. An extended review of the literature and possible discrepancies on reported results are presented in Section 2 along with detailed discussion of the hypotheses investigated in this paper. Section 3 outlines the numerical set-up and computational schemes used for the simulations. Section 4 explores the results based on the objectives discussed in Section 3. These results include sensitivity analysis related to boundary conditions and grid density. Comparison between LES and DNS results, obtained using the same grid resolutions, are used to isolate and identify the difficulties associated with modeling of the wake using sub-grid scale models. A discussion on the effect of Re on the wake results is provided in Section 4.4 followed by concluding remarks in Section 5.

2. Differences in results

This section presents the differences between results in the literature for the flow past an infinite span normal flat plate. Inspection of Table 1 suggests two categorizations: the method of investigation (experimental and numerical), and the Re. In the experiments of Fage and Johansen (1927), Kiya et al. (1982) and Leder (1991) Re ranged from 2.8×10^4 to 1.5×10^5. The computational studies of Joshi (1994), Najjar (1994), Najjar and Balachandar (1998), and Narasimhamurthy and Andersson (2009) were in the range of $Re = 250$ to 1000. Global parameters such as mean pressure coefficient ($\overline{C_p}$), mean drag coefficient ($\overline{C_d}$), mean

Table 1
List of all studies of normal thin flat plates, where $\overline{L_w}$ is the mean recirculation length.("2D" refers to the 2D plate simulations, in which spanwise variables are neglected.)

Case	**Re**	*St*	$\overline{\mathbf{L_w}}/\mathbf{h}$	$\overline{\mathbf{C_d}}$	Method	Outlet Condition
Fage and Johansen (1927)	1.5×10^5	0.146	–	2.13	Experiments	–
Fail et al. (1959)[a]	1.5×10^5	0.145	2.82	1.86	Experiments	–
Kiya and Matsumura (1988)	2.3×10^4	0.146	–	–	Experiments	–
Leder (1991)	2.8×10^4	0.14	2.50	–	Experiments	–
Dennis et al. (1993)	$5 - 20$	–	–	–	Experiments	–
Tamaddon-Jahromi et al. (1994)	$126 - 500$	–	–	–	Numerical (2D)	Outflow direction
Joshi (1994)	1000	0.15	2.30	2.47	Numerical	Convective/Neumann
Najjar and Vanka (1995b)	1000	0.132		3.03	Numerical (2D)	Convective Outflow
Najjar and Vanka (1995a)	1000	≈ 0.143	2.55	2.26	Numerical	Convective Outflow
Najjar and Balachandar (1998)	250	0.161	2.35	2.36	Numerical	Convective Outflow
Mazharoglu and Hacsevki (1999)	3.3×10^4	–	–	–	Experiments	–
Julien et al. (2003)	$200 - 220$	–	–	–	Experiments	–
Julien et al. (2004)	220	–	–	–	Numerical (2D)	–
Wu et al. (2005)	$(1.8 - 27) \times 10^3$	–	–	–	Experiments	–
Saha (2007)	$30 - 175$	–	–	–	Numerical (2D)	Convective Outflow
Narasimhamurthy and Andersson (2009)	750	0.168	1.96	2.31	Numerical	Neumann Outflow
Afgan et al. (2013)	750	0.167	1.88	2.29	Numerical	Neumann Outflow
Tian et al. (2014)	1.5×10^5	0.155	≈ 2.25	2.31	Numerical	Nuemann Outflow

[a] The results quoted for Fail et al. (1959) are those of Fage and Johansen (1927) corrected for blockage.