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Experimental investigation on wake characteristics behind a yawed square cylinder

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ABSTRACT

The wake vortical structures of a square cylinder at different yaw angles to the incoming flow ($\alpha = 0°$, 15°, 30° and 45°) are studied using a one-dimensional (1D) hot-wire vorticity probe at a Reynolds number (Re) of about 3600. The results are compared with those obtained in a yawed circular cylinder wake. The Strouhal number (St_N) as well as the mean drag coefficient (C_{D_N}), normalized by the velocity component normal to the cylinder axis, follow the independent principle (IP) satisfactorily up to $\alpha = 40°$. Using the phase-averaging analysis, both the coherent and the remaining contributions of velocity and vorticity are quantified. The flow patterns of the coherent spanwise vorticity (ω_z) display obvious Kármán vortex streets and their maximum concentrations decrease as α increases. Similar phenomena are also shown in the coherent contours of the streamwise (u) and transverse (v) velocities as well as the Reynolds shear stress (uv). The contours of the spanwise velocity (w) and Reynolds shear stress (uw), however, experience an increasing trend for the maximum concentrations with increasing yaw angle. These results indicate an enhancement of the three-dimensionality of the wake and the reduction of vortex shedding strength as α increases. While general similarities to the wake behind a yawed circular cylinder are found in terms of flow features, some differences between the two wakes at different yaw angles are highlighted.

1. Introduction

One of the main concerns about cylindrical structures immersed in a fluid flow is that the alternate shedding of vortices from the structures and hence the resultant time dependent forces may lead to structure vibration. With increasing use of slender structures of a square cross-section in engineering, significant research on square cylinder wakes has been conducted (e.g. Lyn et al., 1995; Nakagawa et al., 1999; Sohankar et al., 1999; Saha et al., 2000, 2003; Oudheusden et al., 2005; Ozgoren, 2006; Tong et al., 2008; Sheard et al., 2009). In general terms, the description for the flow around a circular cylinder is also believed to be valid for flow around a square cylinder at Reynolds numbers (Re $= U_\infty d/\nu$, where U_∞ is the free streamwise velocity, d is the diameter of the cylinder and ν is the kinematic viscosity of the fluid) less than 100 (Sohankar et al., 1999). However, at high Re, the sharp corners on the square cylinder play a significant role in the evolution

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of flow instabilities and other flow characteristics. The wake of a square cylinder is characterized by fixed separation points, which are distinct from the continuous-curvature cross-section with oscillating separation points, typically represented by the circular cylinder (Alam et al., 2011). A numerical study on the wake of a square cylinder by Saha et al. (2003) showed that at Re of about 175, the three-dimensional structure is formed with intermittent large-scale irregularities as a result of vortex merging in the spanwise direction or due to the phase variations within the large coherent structures. The values of the Strouhal number and the time-averaged drag coefficient are closely associated with each other over a given range of Re = 150–500, reflecting the spatial structure of the wake. Besides, these findings were also in good agreement with the three-dimensional modes of transition that are well-known in the circular cylinder wake. Through the two-dimensional (2D) and three-dimensional (3D) unsteady flow simulations past a square cylinder with zero incidence at moderate Reynolds numbers (Re = 150–500), Sohankar et al. (1999) concluded that the transition from the stable 2D laminar shedding flow to 3D flow appears between Re = 150 and 200. The Strouhal number decreases and the mean drag coefficient increases with Reynolds number, which is opposite to the circular cylinder. The difference is attributed to the fact that the separation always occurs at the upstream corners of the square cylinder and it is independent of time, whereas the circular cylinder has separation points varying with time. A linear stability analysis was employed successfully to analyze the 3D transition of a square cylinder wake by Blackburn and Lopez (2003) and Blackburn and Sheard (2010). The former found a quasi-periodic intermediate wavelength mode between two synchronous instability modes with long and short spanwise wavelengths, which may be a general scenario for three-dimensional instabilities of the time-periodic wakes generated by two-dimensional bluff bodies. The latter examined the effect of symmetry breaking of the vortex street wake on quasi-periodic secondary instabilities, where the symmetry is broken by a small fixed rotation of the square cylinder about its axis. It is found that at a small rotation angle of 7.5°, the quasi-periodic mode is replaced by a subharmonic one which starts to bifurcate from the two-dimensional base state at moderate rotation angles of 12–26°.

Nakagawa et al. (1999) carried out an experimental study with a laser Doppler velocimetry on the turbulence around a square cylinder at Re = 3000. The time-averaged and phase-averaged statistics showed that the turbulent intensities on the centerline of the wake reach their maxima near the stagnation points of the recirculation region. The contributions from the coherent component of both turbulent kinetic energy and Reynolds shear stress to the time-averaged ones are dominant, compared with those from the incoherent component. Moreover, the kinetic energy of the free stream flow is transferred mainly to the coherent structure near the cylinder and the coherent vortices feed the incoherent turbulence at the downstream region. Saha et al. (2000) conducted hot-wire measurements in the wake of a square cylinder at $Re + 8700$ and 17,625, showing that the peak on the streamwise velocity spectrum becomes broader along the streamwise direction due to the energy transported from the time-averaged streamwise velocity to the small-scale structures. The peak of the transverse velocity spectrum is observable over the whole measured range. However, the broadening spectrum in the far wake indicates the decay of the coherent structures in the flow field and an evolution towards the fully three-dimensional state. Using a digital particle image velocimetry (PIV), experiments on a square cylinder wake in an open-circuit wind tunnel for $550 \leq \mathrm{Re} \leq 3400$ were conducted by Ozgoren (2006) to characterize instantaneous as well as phase-averaged signals of both velocity and vorticity in the wake. It was found that the Strouhal number and the wake patterns were dependent on the cross-section of the cylinder as well as the Reynolds number. Owing to the fixed separation points of a square cylinder, the flow separation and recirculation regions had an increasing effect on the length scales in both the streamwise and the transverse directions, i.e., the increase of the size of the wake region and the distance between oppositely signed vortices. The results also indicated that predominant features of instantaneous and phase-averaged vortices were closely related. Therefore, both of them can be used as representative characteristics of the flow.

As flow approaches a cylinder at a yaw angle α (the angle between the flow direction and the plane which is perpendicular to the cylinder axis, so $\alpha = 0°$ corresponds to the cross-flow case while $\alpha = 90°$ corresponds to the axial flow case), the flow velocity component in the cylinder axial direction would affect the vortex shedding characteristics. For a yawed circular cylinder, it has been found that over a certain range of cylinder yaw angle the Strouhal number and the drag coefficient, normalized by the velocity component perpendicular to the cylinder, i.e. $\mathrm{St}_N = f_0 d/U_N$ and $C_{DN} = F_x/(1/2\rho U_N^2 d)$, where f_0 is the vortex shedding frequency, F_x is the in-line force and $U_N = U_\infty \cos \alpha$ is the velocity component normal to the cylinder axis, are the same as those when the cylinder encounters a normal incidence flow. This is generally known as the Independence Principle (IP), the cross flow principle or the cosine law. The validity of IP in steady flow past a yawed circular cylinder has been investigated extensively both experimentally (Surry and Surry, 1967; King, 1977; Ramberg, 1983; Thakur et al., 2004; Zhou et al., 2009, 2010; Franzini et al., 2013; Gallardo et al., 2014) and numerically (Marshall, 2003; Lucor and Karniadakis, 2004; Zhao et al., 2009), even though there are some discrepancies with the angle range over which IP is valid. In an experimental study on a stationary yawed circular cylinder (α = 0–60°), Ramberg (1983) concluded that the vortex shedding frequency was greater than that expected from the IP since the measured Strouhal number of the yawed cylinder was larger than the theoretical value when taking the yaw angle into consideration, which invalidates the IP. Marshall (2003) investigated the wake dynamics of a yawed circular cylinder in a quasi-two-dimensional idealization with a perturbation analysis. It was found that the instability of the vortex street and the breakdown of IP at large yaw angles for fully three-dimensional flows might be led by the cross-stream vortex sheets and the streamwise flow deficit. Lucor and Karniadakis (2004) numerically studied a yawed circular cylinder by comparing forces, cylinder responses and reduced velocity for different yawed angles. Their results indicated that for large angle of attack, such as $\alpha = -60°$ and $-70°$, the vortex shedding angle is smaller than the yaw angle and the IP is not valid. The base pressure is lower and hence the drag coefficient is higher than the value predicted by the IP. Similarly, a direct numerical simulation for flow past a circular