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Flow behavior around a square cylinder subject to modulation of a planar jet issued from upstream surface

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ABSTRACT

The flow behavior in the up- and downstream regions of a square cylinder subject to the modulation of a planar jet issued from the cylinder's front surface was studied using the laser-assisted smoke flow visualization method and hot-wire anemometer measurement. Reynolds numbers were from 1628 to 13 000. The drag force experienced by the square cylinder was obtained by measuring the surface pressures on the up- and downstream faces. The temporally evolving smoke flow patterns in the up- and downstream regions were synchronously revealed through the smoke flow visualization. The frequency characteristics of the instability waves in the up- and downstream regions were synchronously detected by the two hot-wire anemometers. Four characteristic flow modes were observed within the different ranges of the injection ratios. At the low injection ratios ($IR < 1$), the '*swinging jet*' appeared. The jet swung periodically leftward and rightward and formed a fluid bubble on the front surface. The fluid bubble contained a pair of counter-rotating vortices and presented a periodic variation in its height. At moderately low injection ratios ($1 < IR < 4.3$), the '*deflected oscillating jet*' appeared. The jet was deflected in either the left or the right direction and wrapped around one of the edges of the square cylinder. Both the swinging and oscillating motions of the jet in the *swinging jet* and *deflected oscillating jet* modes were induced by the periodic feedback pressure signals generated by the vortex shedding in the wake. At the moderately high ($4.3 < IR < 8.3$) and high ($IR > 8.3$) injection ratios, the '*deflection jet*' and '*penetrating jet*' appeared. The jet detached from the cylinder's front surface and penetrated a long distance into the upstream region due to large jet momentum. Neither periodic jet oscillation in the upstream region nor vortex shedding in the wake was observed. The drag coefficient was found to be decreasing quickly with increasing the injection ratio.

1. Introduction

Complex flow phenomena, such as flow separation, vortex shedding, and shear-layer instability, appear in the vicinity of a bluff body when a flow passes across the bluff body, such as a circular cylinder, a square cylinder, a sphere and so on. Many studies published in the past decades have discussed the boundary-layer flows, vortex-shedding characteristics, pressure

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Nomenclature

C_D	drag coefficient in x direction
C_{D0}	drag coefficient in x direction at $R=0$
C_p	pressure coefficient
d_{slot}	width of slot for jet injection from front surface of square cylinder, 2 mm
f	frequency of jet oscillation or vortex shedding in cylinder wake
IR	injection ratio ($=u_j/U$)
L	length of square cylinder, 520 mm
L_{slot}	length of jet slot, 492 mm
p	local surface static pressure on square cylinder
p_o	static pressure of freestream
Q_j	flow rate of jet
Re_d	jet Reynolds number based on slot width d_{slot}
Re_w	freestream Reynolds number based on square cylinder side width w
St_w	Strouhal number of vortex shedding based on w ($=fw/U$)
t	evolving time
t^*	non-dimensional time (tU/w)
U	freestream velocity
u	local velocity
u_j	jet velocity at exit ($=Q_j/(L_{slot}\times d_{slot})$)
w	side width of square cylinder, 60 mm
x	Cartesian coordinate in axial direction
y	Cartesian coordinate in cross-stream direction
z	Cartesian coordinate along cylinder axis
Φ	power spectrum density function
ρ	air density
ν	kinematic viscosity of air

distributions, lift, and drag of a square cylinder in freestream (e.g., Vickery, 1966; Lee, 1975; Obasaju, 1983; Tamura and Miyagi, 1999; Saha et al., 2000; Dutta et al., 2003; Lao et al., 2007; Tong et al., 2008; Huang et al., 2010). The flow behaviors are relatively insensitive to Reynolds numbers, but are more sensitive to the incidence angle (Okajima, 1982). The flow characteristics, vortex-shedding frequency, and aerodynamic forces consequently exhibit distinct behaviors at different incidence angles of the square cylinder. Time-averaged or instantaneous flow field in the near wake of a square cylinder in a freestream has been reported by investigators (e.g., Durão et al., 1988; Lyn et al., 1995; van Oudheusden et al., 2005; Ozgoren, 2006; Hu et al., 2006; Kurtulus et al., 2007; Huang et al., 2010; Huang and Lin, 2011).

As discussed in the above paragraphs, the complex flow separation and recirculation behaviors of the square cylinder may induce large aerodynamic forces. Consequently, investigators examined some flow control methods to modulate the flow characteristics. A flow-control method using a control rod was reported by Igarashi (1997), Sarioglu et al. (2005), and Zhang et al. (2005). Between the small control rod and the square cylinder, the rod wake-influenced flow presented two characteristic flow patterns: cavity and vortex shedding. At small incidence angles, when the arrangement of the control rod and the square cylinder induced a cavity-flow pattern between the rod wake and the square cylinder, the drag coefficient of the square cylinder was reduced. At mid-range and large incidence angles, however, the drag of the square cylinder was increased through the installation of the small control rod. Huang et al. (2011) reported the results of using a self-sustained vibration rod method to manipulate the flow characteristics around a square cylinder. Owing to the influence of the vibrating rod, the flow pattern on the agitated surface changed. The critical incidence angle was advanced from its natural state of 15–11°. The drag was reduced by about 25%.

Many flow control methods for reducing or suppressing the periodic wake instabilities downstream of a bluff cylinder have been reported by investigators in the last few decades. These include flapping foil, helical wires, base bleed, splitter plate, corner modification, suction/blowing, and acoustic excitation. The practice of using a slot jet injection from the rear surface to control the flow in the wake of a square cylinder has drawn the attention of investigators during the last two decades. Koutmos et al. (1996) presented the results of a numerical study on such a flow. They found that a system of four counter-rotating vortices appeared behind the square cylinder because the planar jet velocity was not large enough to penetrate the wake recirculation. As the planar jet velocity became large enough to penetrate the wake recirculation, the periodic vortex shedding turned into irregular unsteadiness. Kim et al. (2003) presented the computational results of using the planar jet injection from the rear surface of a square cylinder in a confined channel to manipulate the vortex shedding in the wake. They found that the jet penetrates the main vortices shed from the square cylinder, resulting in significant changes in the flow and scalar fields. Regions of intense scalar are formed along the streamlines from the jet exit and the oscillation of the force on the cylinder eventually disappears as the jet velocity approaches the inlet velocity. Koutmos et al. (2004) performed computational and experimental studies on the wake flow of a two-dimensional square cylinder with planar jet injection from its base into the vortex formation region. They confirmed that the periodic wake instabilities disappeared as the injection ratio (i.e., the jet to free stream velocity ratio) is greater than about one. Akansu and Firat (2010) conducted experimental studies on the control of flow around a square prism by slot jet injection from the rear surface. They found that an increase in the injection ratio up to a certain value caused important pressure recovery in the wake. With the further increase of the injection ratio, the slot jet split the near wake like a splitter plate.

The flow control method using slot jet injection from the front surface of the square cylinder was rarely found in the literature. Kim et al. (2003) performed a numerical study on a slot jet injecting from the front surface of a square cylinder in a laminar freestream. They mentioned that the high-pressure region on the front face of the square cylinder was pushed upstream by the jet. As a result, the drag force exerted on the cylinder was significantly reduced by 42.7% when the injection ratio was greater than one. Following Kim et al.'s clue, the present work performed an experimental study on the flow field variations around a square cylinder subject to the influence of a slot jet injecting from the front surface of the cylinder.