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Flow characteristics and drag force of a square cylinder in crossflow modulated by a slot jet injected from upstream surface

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ABSTRACT

The flow characteristics and drag force of a square cylinder with a front jet injection were experimentally investigated in a wind tunnel. The evolution process of the characteristic flow patterns was recorded by the laser-assisted smoke flow visualization method. The time-averaged velocity fields measured by particle image velocimetry (PIV) were applied to analyze the velocity vectors, streamline patterns, vorticity contours, velocity distributions, and time histories of instantaneous velocities around the upstream region of the square cylinder. The drag force experienced by the square cylinder was obtained by measuring the surface pressures on the front and rear faces. The results show that the jet emitted from the upstream surface of the square cylinder periodically swings left-and-right in the experimental range of injection ratio $\leqslant 0.9$. In the time-averaged velocity field, the jet flow impinges the freestream at a four-way saddle and subsequently bifurcates into two streams; one stream goes toward the left edge of the upstream surface, while the other stream directs toward the right edge of the upstream surface. Two recirculation regions formed above the upstream surface of the square cylinder are enclosed by those two streams. The vorticity contours around the upstream surface of the square cylinder are characterized by two adjacent vorticity-concentrated areas of opposite signs. The time histories of the instantaneous velocities around the four-way saddle, jet exit, and shear layer of the swinging jet represent periodic oscillation. This characteristic oscillation frequency is dominated by the wake instability. The recirculation regions formed above the cylinder's upstream surface prevent impingement from the freestream. Consequently, the surface pressure coefficients on the upstream surface of the square cylinder are reduced. This reduction in the surface pressure coefficient decreases the drag force acting on the square cylinder.

1. Introduction

The study of the flow characteristics around the square cylinder in a uniform flow is important for industrial applications, such as architectural structures and heat exchangers. Many studies published in past decades have discussed the flow characteristics and aerodynamic performances of a square cylinder in freestream [1–9]. When a flow passes across a square cylinder, the flow characteristics, vortex-shedding frequency, and aerodynamic forces exhibit distinct behaviors at different ranges of incidence angles of the square cylinder. The flow behaviors are relatively insensitive to Reynolds numbers, but are more sensitive to the incidence angle. The complex flow separation and recirculation behaviors around the square cylinder may induce large aerodynamic forces. Investigators, therefore, have developed some passive and active flow control methods to modulate the flow characteristics and to suppress the drag force asserting on the cylinder.

Tamura and Miyagi [10] found that the separated shear layers approaching the side surface of the square cylinders with chamfered and rounded corners could promote reattachment and therefore reduce the drag force. Igarashi [11], Sarioglu et al. [12], and Zhang et al. [13] installed a rigid small circular rod at a distance upstream of the square cylinder to control the flow behaviors. They observed that the flow between the control rod and the square cylinder presented cavity and vortex shedding modes. When a cavity-flow pattern appeared between the rod wake and the square cylinder, the drag coefficient of the square cylinder was reduced. Huang et al. [14] developed a self-sustained vibration rod to control the flow around a square cylinder. The rod vibration

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Nomenclature

A_j	slot jet area ($=d_{slot} \times L_{slot}$)
C_D	drag coefficient excluding jet momentum
$C_{D,j}$	drag coefficient including jet momentum
C_p	pressure coefficient
f	frequencies of jet and wake
d_{slot}	width of slot for injecting a jet from upstream surface of square cylinder, 2 mm
H_j	height of jet penetration
L	length of square cylinder, 520 mm
L_{slot}	length of jet slot, 492 mm
M_j	jet momentum ($=\rho_j \times u_j^2 \times A_j$)
Q_j	flow rate of jet
R	injection ratio ($=u_j/u_w$)
Re_j	jet Reynolds number based on jet slot width d_{slot}
Re_w	freestream Reynolds number based on side width of square cylinder w
t	evolution time
t^*	non-dimensional time ($=tu_w/w$)
u	instantaneous streamwise velocity
$\bar{u}$	time-averaged streamwise velocity
u_w	freestream velocity
v	instantaneous transverse velocity
V	instantaneous velocities simultaneously detected at up- or downstream regions of square cylinder
$\bar{v}$	time-averaged transverse 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
ρ_j	density of jet fluid
ν_j	viscosity of jet fluid
ν_w	viscosity of freestream
Φ	power spectrum density function of velocity fluctuation
Ω_z	vorticity flow field in z-direction $\left(=\frac{\partial \bar{v}}{\partial x}-\frac{\partial \bar{u}}{\partial y}\right)$

induced by fluid–solid interaction significantly changed the flow patterns around the square cylinder, and therefore reduced the drag by about 25%. Ali et al. [15,16] studied the flow around a square cylinder subject to the influence of a splitter plate by numerical method. The drag force decreased with an increase in the length of the splitter plate due to the suppression of vortex shedding in the cylinder wake.

Koutmos et al. [17] performed computational and experimental studies on the wake flow of a two-dimensional square cylinder with a planar jet injected from the cylinder base into the vortex formation region. They confirmed that the periodic wake instabilities disappeared when the injection ratio (i.e. the jet to freestream velocity ratio) is greater than about one. Akansu and Firat [18] conducted experimental studies on the control of flow around a square prism by a slot jet emitted from the cylinder base. They found that increasing the injection ratio up to a certain value could cause important pressure recovery in the wake. Çuhadaroğlu et al. [19], Çuhadaroğlu [20], and Turhal and Çuhadaroğlu [21] studied the effects of uniform injection and suction through a porous square cylinder on flow field and aerodynamic parameters. They found that increasing the injection/suction velocity would decrease the drag coefficient.

The flow control method of using a slot jet injection from the upstream surface of the square cylinder was rarely found in the literature. A slot jet injected from the upstream surface of a square cylinder in a laminar freestream was studied by Kim et al. [22]. They reported that the high-pressure region on the upstream face of the square cylinder was pushed upstream by the control jet. As a result, the drag force exerted on the cylinder was reduced. Huang et al. [23] studied the flow behavior in the upstream and downstream regions of a square cylinder subject to the modulation of a planar jet issued from the cylinder's upstream surface. Four characteristic flow modes were observed in the domain of the injection ratio and the freestream Reynolds number. The *swinging jet* mode appeared at the low injection ratios R smaller than about 1. 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. The *deflected oscillating jet* mode appeared at the moderately low injection ratios within $1 < R < 4.3$. The jet was deflected in either the left or the right direction and wrapped around one of the edges of the square cylinder. At the moderately high and high injection ratios, the *deflection jet* mode ($4.3 < R < 8.3$) and *penetrating jet* mode ($R > 8.3$) appeared. The jet detached from the cylinder's front surface and penetrated a long distance into the upstream region due to large jet momentum. The drag coefficient decreased with an increase in the injection ratio.

The flow behavior, vortex shedding, and drag force of a square cylinder with a slot jet issued from the cylinder's upstream surface have been investigated in the previous studies by flow visualization, hotwire anemometer, and pressure measurement. However, the detailed dynamics of the velocity field around the upstream surface of the square cylinder still remain unclear. In the present work, the qualitative and quantitative flow characteristics around the cylinder's front surface are investigated in the range of swinging jet mode ($R < 1$) by using flow visualization and high-speed particle image velocimetry (PIV). The velocity vectors, streamline patterns, vorticity contours, velocity distributions, instantaneous velocities, surface pressure coefficient distributions, and drag coefficients are presented and discussed. The results will help to better understand the physical mechanism of the front jet injection-controlled square cylinder flow.

2. Experimental methods

2.1. Apparatus

A closed-return wind tunnel was used for experiments. The test section of the wind tunnel was 600 mm × 600 mm × 1200 mm in width, height, and length, respectively. The bottom wall of the test section was made from one polished aluminum-alloy plate. For flow visualization, the upper and side walls of the test section were made from three transparent acrylic panels. A hot-wire anemometer, which was specially calibrated by a Pitot tube along with a high-precision pressure transducer, was used to detect the freestream velocity u_w. The maximum freestream velocity u_w used for the experiment was 0.54 m/s, which corresponded to a Reynolds number $Re_w = 2100$. The selection of upper limit of Reynolds number in the study is to compare with the previous study of Huang et al. [23]. The turbulence intensity within the experimental range of u_w was less than 0.6%.

A hollow square cylinder, made of aluminum alloy (6061TET62), was mounted vertically in relation to the flow direction in the test section. The square cylinder had a side width of