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Interactions of tandem square cylinders at low Reynolds numbers

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Abstract

Two identical square cylinders were installed in tandem in a vertical water tank. The effects of the Reynolds number, spacing ratio and rotation angle of the downstream cylinder on flow characteristic modes, drag coefficients and vortex shedding properties were studied. The particle image velocimetry (PIV) scheme was applied to examine and classify the flow field into three characteristic modes: vortex sheet of the single mode, reattached mode and binary mode. Via topological analysis, the velocity vector field, streamline pattern, and the properties of these flow modes are presented and discussed. In the viscosity-dominant flow field, the Strouhal number decreases as the Reynolds number increases. However, in the inertia-dominant flow field, the Strouhal number increases with the Reynolds numbers and approaches a constant for high Reynolds numbers. The maximum drag coefficient in the vortex sheet of reattached mode is approximately 76% lower than that in the single square cylinder case.

Keywords: Tandem square cylinders; PIV; Topological analysis; Vortex shedding

1. Introduction

Two-dimensional square cylinders at a low Reynolds number have attracted considerable interest and have been extensively studied for numerous applications such as in buildings, trailer trucks, bridge piers, monuments, and heat exchangers. Numerous studies employ qualitative or quantitative flow visualization techniques such as hot wire and laser doppler velocimetry (LDV) to analyze the near-wake flow field. Previous studies determined that unsteady effects appeared when the flow moved around a cylinder. These unsteady phenomena have been identified in the forms of separation, reattachment bubble, shear-layer instability, or vortex shedding [1–3].

Many studies have investigated vortex shedding in the wake, and the aerodynamic performance when fluid flows around a square cylinder. Lyn et al. [4] utilized the ensemble average statistics approach to study turbulent near-wake flow around a square cylinder. Two features were identified. (i) A double peak in the shear Reynolds stress distribution associated with a vortex structure was found in the wake, and one peak occurred in the vortex peak regions. (ii) Turbulence flow was generated close to the vortex center due to high normal Reynolds stresses. Okajima [5] analyzed vortex shedding frequency of rectangular cylinders by considering the effects of aspect ratios when $70 < Re < 2 \times 10^4$. Okajima concluded that the Strouhal number is 0.13 when Reynolds numbers are 10^4–2×10^4, and an abrupt change to flow pattern and a sudden discontinuity in Strouhal number curves were observed when the aspect ratio was 2 or 3. Dutta et al. [6] utilized a hot wire anemometer and X-wire to probe the unsteady velocity profile behind a square cylinder. They summarized three features. (i) When inclinations were >0°, the points of separation move downstream and then drag force decreases. Therefore, the Strouhal number increases. (ii) Velocity fluctuations decay in the downstream direction, and the

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Nomenclature

D	chord length of square cylinder, 3 cm in this study	Ro	Roshko number of vortex shedding ($= f\,D^2/\nu$)
C_D	drag coefficient ($=D/qbC$)	St	Strouhal number of vortex shedding ($= f\,D/u_\infty$)
$f(u')$	probability density function of fluctuation velocities	u_∞	x-component of local instantaneous velocity
f	frequency of instabilities in wake region (Hz)	u'	fluctuating velocity
L	streamwise spacing between the centers of two square cylinders	x	streamwise coordinate
q	dynamic pressure of free stream ($= \frac{1}{2}\rho u_\infty^2$)	y	spanwise coordinate
R_τ	autocorrelation coefficient of fluctuation velocities $\left(= \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2}}\right)$	θ	rotation angle
Re	Reynolds number of square ($= u_\infty D/\nu$)	ρ	density of water stream
		ν	kinetic viscosity of water stream
		Φ	power spectrum of fluctuating velocities
		τ_1	time shift for calculating autocorrelation coefficient of fluctuation velocities

slowest decay rate is at $\theta = 45°$. Additionally, the cross-correlation function strongly depends on cylinder orientation before it diminished to zero along the wake centerline. (iii) The velocity spectra are dominated by vortex shedding frequency. Additionally, Dutta et al. determined $C_D = 2.1$ by utilizing the momentum integral equation.

Many studies have applied a two cylinders flow control mechanism to lower drag force. Kolar et al. [7] employed a laser-Doppler velocimeter to probe the ensemble average characteristics of turbulent near-wake flow around two side-by-side identical square cylinders when $Re \approx 23{,}100$. They determined that enhanced vortex motion and average vortex speed in the base region are very high, even in the eventual near-wake equilibrium state. Kolar et al. also found that the Strouhal number is higher than that for the case with one-square-cylinder due to the contribution of increased turbulence kinetic energy. Sakamoto et al. [8], who investigated flow field around two tandem square cylinders, discovered that regular shedding of vortices from the upstream cylinder is suppressed when $L/D < 4$, and

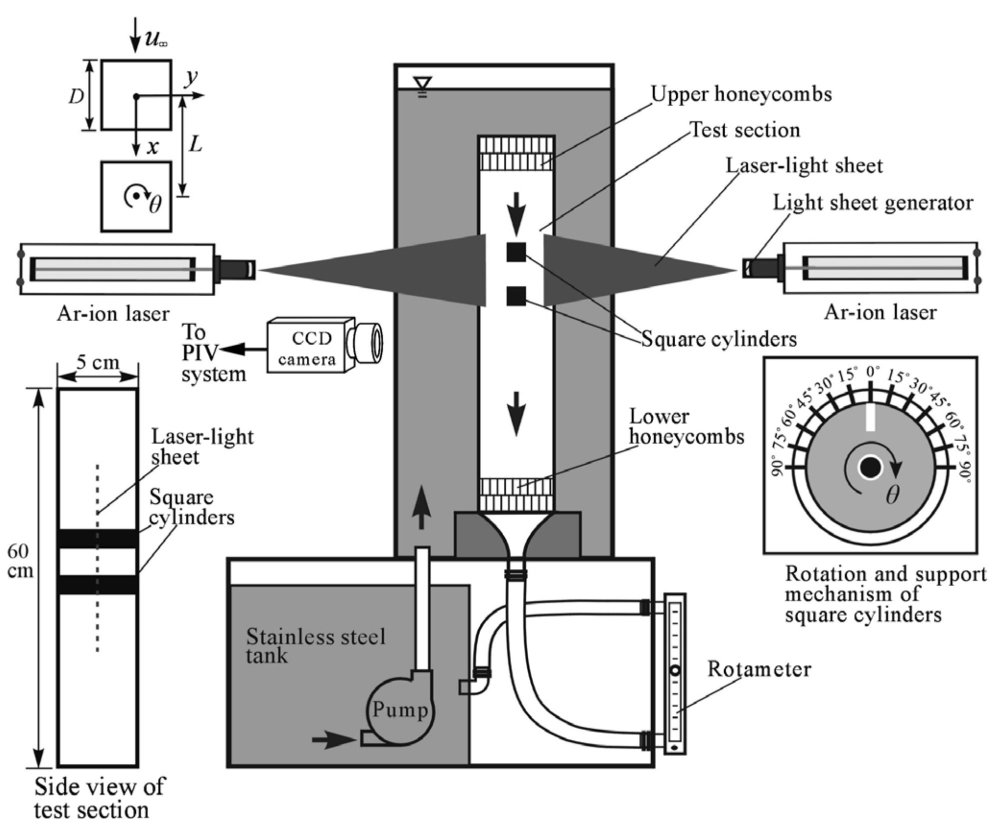

Fig. 1. Experimental setup.