ELSEVIER

Journal of Fluids and Structures 23 (2007) 339–347

JOURNAL OF FLUIDS AND STRUCTURES

www.elsevier.com/locate/jfs

Special brief communication

Phase lag between vortex shedding from two tandem bluff bodies

Md. Mahbub Alam*, Y. Zhou

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Received 7 July 2006; accepted 24 November 2006
Available online 23 January 2007

Abstract

This paper presents a work on the phase lag (ϕ) between vortex sheddings from two tandem cylinders of various shapes and its influence on fluctuating lift on the upstream cylinder. A differential equation of ϕ, $\mathrm{d}\phi = [4\pi f_s/(2V_c - \mathrm{d}V_c)]\,\mathrm{d}x$, is derived, where f_s is the vortex shedding frequency, V_c is the convective velocity of vortices, and x is the downstream distance from the upstream cylinder. Applying the condition $\phi = 2\pi$ at $L^* = L_c^*$, as obtained from experimental data, the equation yields $\phi = 2.44\pi\,\mathrm{St}(L^* - L_c^*) + 2\pi$, where St is the Strouhal number, L^* is the normalized cylinder center-to-center spacing and L_c^* is the critical spacing defined as the minimum L^* at which the upstream cylinder could shed vortices in the gap between the cylinders. This relationship agrees well with experimental data previously reported as well as presently measured.

Keywords: Tandem bluff bodies; Phase lag; Critical spacing; Strouhal number

1. Introduction

Two cylinders in proximity do not shed vortices independently; for a given center-to-center spacing L^*, there is a definitive phase lag (ϕ) between vortex shedding from one cylinder and that from the other (Sakamoto et al., 1987; Alam et al., 2003). In this paper, an asterisk denotes normalization by the cylinder characteristic dimension, d. This phase lag information is useful since ϕ may have a profound influence upon forces on the cylinders (Alam et al., 2006).

Flow around two tandem circular cylinders may be classified into three regimes based on center-to-center spacing L^* (Zdravkovich, 1987): (i) an extended-body regime, where L^* ranges from 1 to 1.5 and the two cylinders are so close to each other that the free shear layers separated from the upstream cylinder overshoot the downstream one; (ii) a reattachment regime, where L^* is between 1.5 and 4 ($= L_c^*$), and the shear layers reattach on the downstream cylinder; (iii) a co-shedding regime, where $L^* \geqslant L_c^*$ and the shear layers roll up alternately, forming a vortex street in the gap between as well as behind the cylinders. In the co-shedding regime, the frequency of vortex shedding from one cylinder is identical to that from the other (Xu and Zhou, 2004; Alam and Sakamoto, 2005; Zhou and Yiu, 2006). Vortex shedding from the downstream cylinder is triggered by the arrival of vortices generated by the upstream cylinder (Papaioannou et al., 2006). Naturally, ϕ is dependent on the Strouhal number ($\mathrm{St} = f_s d/U_\infty$, where f_s is the vortex shedding frequency and U_∞ is the free-stream velocity) and the convection velocity of upstream-cylinder-generated

*Corresponding author. Tel.: +852 27667813; fax: +852 23654703.
E-mail addresses: mmalam@polyu.edu.hk, Alamm28@yahoo.com (M. Mahbub Alam).

0889-9746/$ - see front matter
doi:10.1016/j.jfluidstructs.2006.11.003

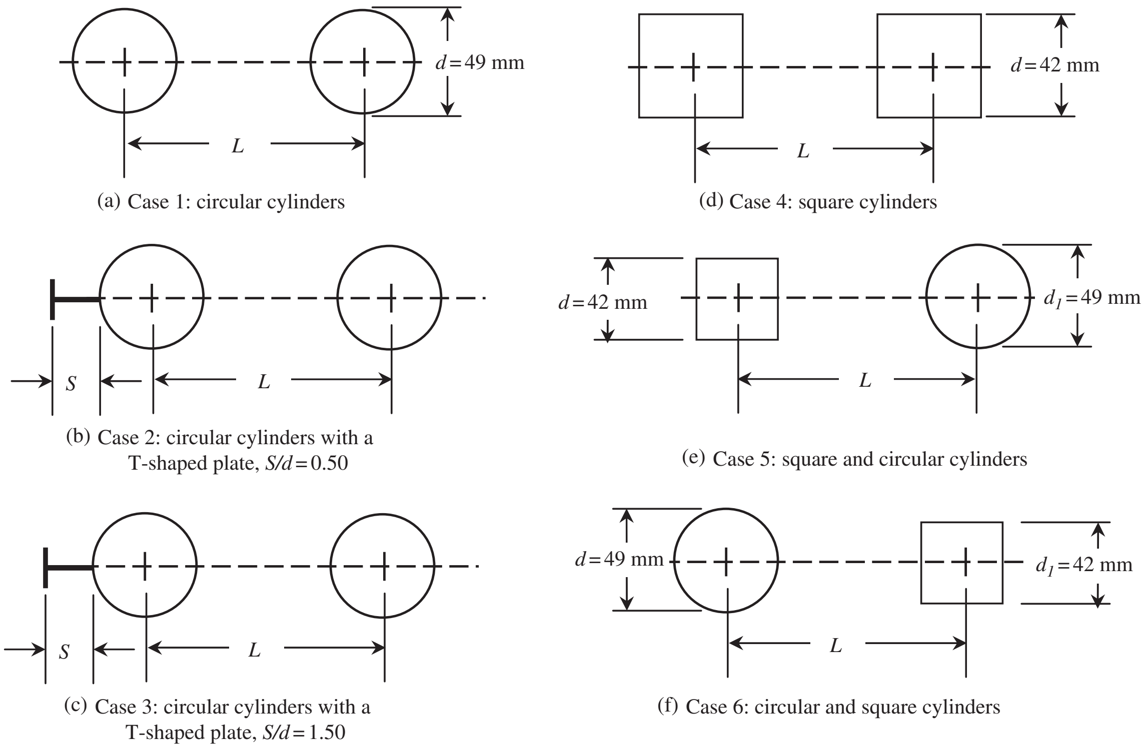

Fig. 1. Cases studied previously and presently. Case 1, Re $= 6.5 \times 10^4$ (Alam et al., 2003, 2006); Cases 2 and 3, Re $= 6.5 \times 10^4$ (Alam et al., 2006); Case 4, Re $= 5.6 \times 10^4$ (Sakamoto et al., 1987); Cases 5 and 6, Re $= 4.7 \times 10^4$ and 5.5×10^4 (based on the upstream cylinder dimension), respectively. Flow is from left to right.

vortices as well as L^*. Previous experimental data (e.g., Sakata and Kiya, 1983; Sakamoto et al., 1987; Alam et al., 2003, 2006) showed that, in the case of two tandem cylinders, ϕ varies linearly with increasing L^*. However, the relationship between ϕ and the frequency and convection velocity of upstream-cylinder-generated vortices has not been established. Furthermore, the possible correlation between ϕ and forces on cylinders has not previously been addressed.

In this study, an empirical correlation between ϕ, St and L^* is proposed based on experimental data measured presently and those in the literature. A theoretical analysis is also conducted; the derived relationship of ϕ, St and L^* is in excellent agreement with the empirical correlation. Furthermore, correlation between fluctuating (r.m.s.) lift C'_L and ϕ is discussed. Experimental results of six cases shown in Fig. 1 are analyzed. Case 1 is two plain circular cylinders (Alam et al., 2003, 2006). Cases 2 and 3 are two circular cylinders with a T-shaped plate placed upstream of the upstream cylinder (Alam et al., 2006). The head width of the T-shaped plate is 5 mm when the cylinder diameter is 49 mm. The presence of the T-shaped plate modifies the vortex shedding frequency of the upstream cylinder. Case 4 is two plain square cylinders of a characteristic height $d = 42$ mm (Sakamoto et al., 1987). Cases 5 and 6 are a combination of square and circular cylinders of $d = 42$ and 49 mm, respectively.

2. Experimental details

The quantities C'_L, St and ϕ for Cases 1–3 were measured by Alam et al. (2003, 2006) and those for Case 4 by Sakamoto et al. (1987). The wind tunnels used were introduced in the relevant papers. The fluctuating lift coefficient C'_L was measured, using load cells, over a length of about 1d at mid-span of the cylinders. The load cells and C'_L measurement were detailed in Alam et al. (2006), Sakamoto et al. (1987), Sakamoto and Oiwake (1984) and Sakamoto et al. (1994). St was estimated from the power spectral analysis of fluctuating lift forces on the cylinders. For Cases 5 and 6, St was measured by Alam and Sakamoto (2005), and ϕ was presently estimated from the cross-correlation between the simultaneously measured fluctuating lift forces of the upstream cylinder, L_{fU}, and the downstream cylinder, L_{fD},

$$R_{L_{fU}L_{fD}}(\phi) = \frac{\overline{\{L_{fU}(t)\}\{L_{fD}(t+\phi)\}}}{[\overline{\{L_{fU}(t)\}^2}]^{1/2}[\overline{\{L_{fD}(t+\phi)\}^2}]^{1/2}}, \tag{1}$$

where t is time. For Cases 1–4, ϕ was estimated following the same procedure. Note that ϕ was calculated only for $L^* \geqslant L^*_c$ (the co-shedding regime) for all cases; for $L^* < L^*_c$ the upstream cylinder does not shed vortices and hence ϕ is not well defined. L^*_c was decided from the jump in both time-averaged and fluctuating fluid forces on the cylinders. The increment ΔL^* of L^* in the measurement of forces was of about 0.5, implying a maximum possible error of ± 0.25 in L^*_c.

For the present cases, experiments were conducted in a closed-circuit wind tunnel. Details of the wind tunnel for the presently measured ϕ were given in Alam and Sakamoto (2005). In order to check the spanwise uniformity and separation of the flow on the circular cylinders, circumferential time-averaged and fluctuating pressures on the surface of an isolated cylinder were measured at sections $z = 0$ (mid-section), ± 35 and ± 80 mm. St from the fluctuating pressure at these sections was also estimated. The results showed that the time-averaged and fluctuating pressure distributions as well as St at the five different sections were the same, confirming a parallel vortex shedding from the cylinder (Williamson, 1989, 1996).

3. Experimental results

3.1. Correlation between fluctuating lift C'_L and phase lag ϕ

Fig. 2 presents the variations of ϕ for the six cases, either collected from the literature or presently examined. Note that in the co-shedding regime vortex shedding from the downstream cylinder is identical to that from the upstream cylinder for all cases (Sakamoto et al., 1987; Alam et al., 2003, 2006), including Cases 5 and 6, where the upstream and downstream cylinders are different (Alam and Sakamoto, 2005). The values of St for Cases 1–6 are approximately 0.2, 0.225, 0.237, 0.13, 0.12 and 0.18, respectively; St was calculated based on the characteristic height of the upstream cylinder. Interestingly, these values always approach the dimensionless frequencies of vortex shedding from the

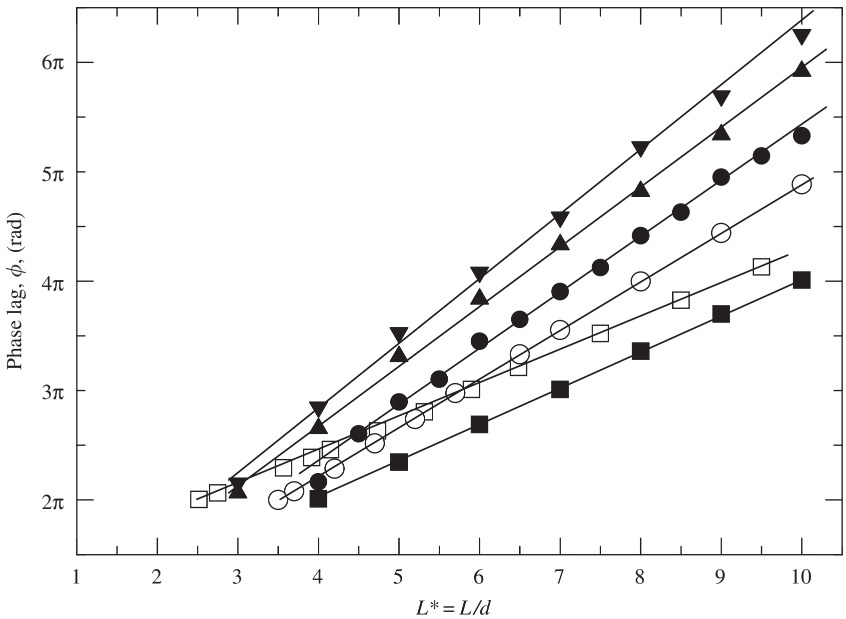

Fig. 2. Phase lag between fluctuating lift forces on the two cylinders: (●) Case 1, Re = 6.5 × 10^4 (Alam et al., 2003, 2006); (▲) Case 2, Re = 6.5 × 10^4 (Alam et al., 2006); (▼) Case 3, Re = 6.5 × 10^4 (Alam et al., 2006); (■) Case 4, Re = 5.6 × 10^4 (Sakamoto et al., 1987); (□) Case 5, Re = 4.7 × 10^4 (present); and (○) Case 6, Re = 5.5 × 10^4 (present). In the literature cited here, L^* was defined as the gap spacing between the cylinders, as opposed to center-to-center spacing adopted presently.

upstream cylinder if the downstream cylinder is removed. For Cases 2 and 3, the placement of the T-shaped plate modifies St of the upstream cylinder to 0.225 and 0.237, respectively. The observation reinforces previous reports (Sakamoto et al., 1987; Alam and Sakamoto, 2005; Papaioannou et al., 2006) that vortex shedding from the downstream cylinder is triggered by the arrival of upstream-cylinder-generated vortices. The ϕ versus L^* relationship is linear for all cases (see Fig. 2).

Fig. 3 presents a collection of C'_L values on the upstream cylinder (circular) versus L^* from the literature. It is evident that C'_L is highly dependent on L^* and hence on ϕ in view of the linear ϕ versus L^* relationship (Fig. 2). A concurrent plot of C'_L and ϕ (Fig. 4(a)) is given for representative Case 3. The maximum and minimum of C'_L occur at $\phi = 2n\pi$ and $(2n+1)\pi$, respectively (n = 1, 2, 3, …), which correspond to the in-phase and out-of-phase vortex shedding from the two cylinders. In the in-phase mode (Fig. 4(b)), that is, for vortices shed simultaneously from the same side of the two cylinders, shear layer separation from the downstream cylinder may act to accelerate that from the upstream cylinder, thus producing greater C'_L values for the upstream cylinder. On the other hand, in the out-of-phase mode (Fig. 4(c)) when vortices are shed simultaneously from the opposite sides of the two cylinders, the shear layer separation from the downstream cylinder may tend to induce the same-side shear layer separation from the upstream cylinder, which may act to slow down shear layer separation from the opposite side of the upstream cylinder. As a result, C'_L is a

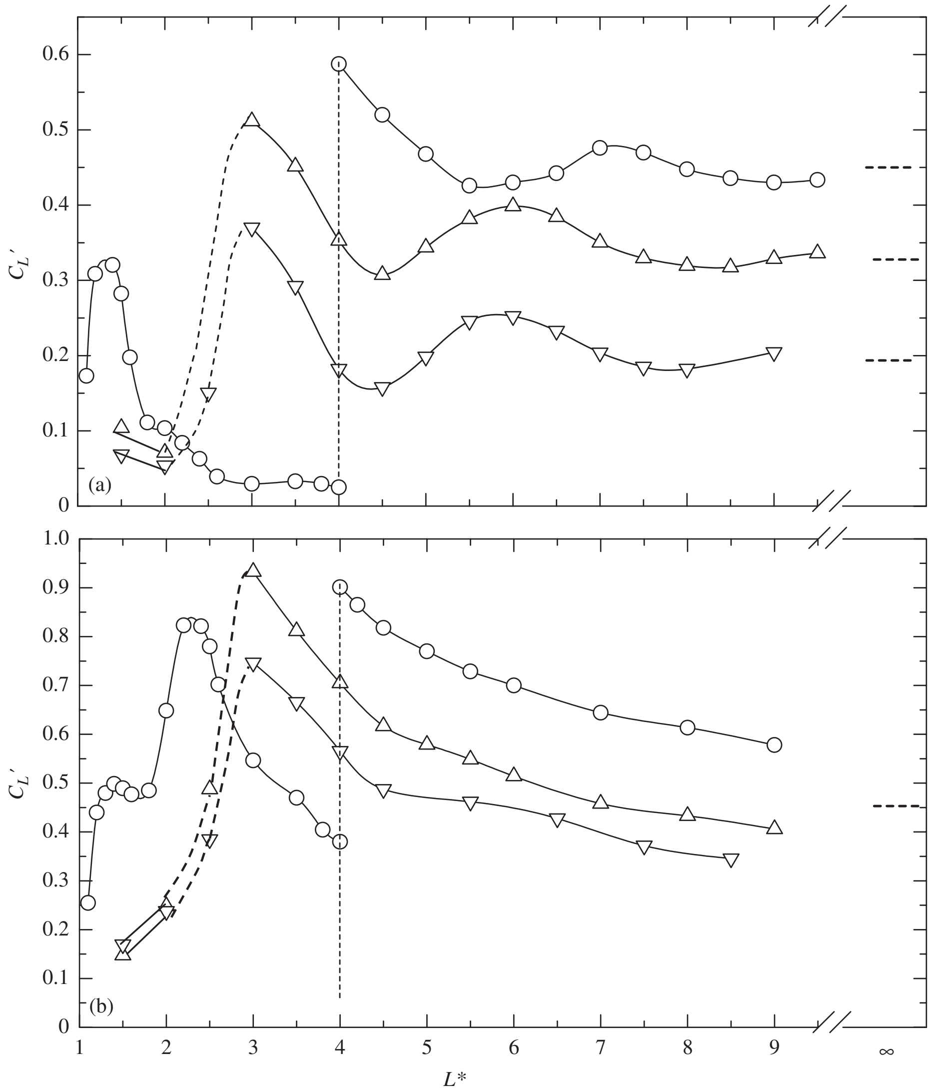

Fig. 3. Effect of L^* on fluctuating lift force on (a) the upstream cylinder, (b) the downstream cylinder: (○) Case 1; (△) Case 2; and (▽) Case 3. Data are from Alam et al. (2006).

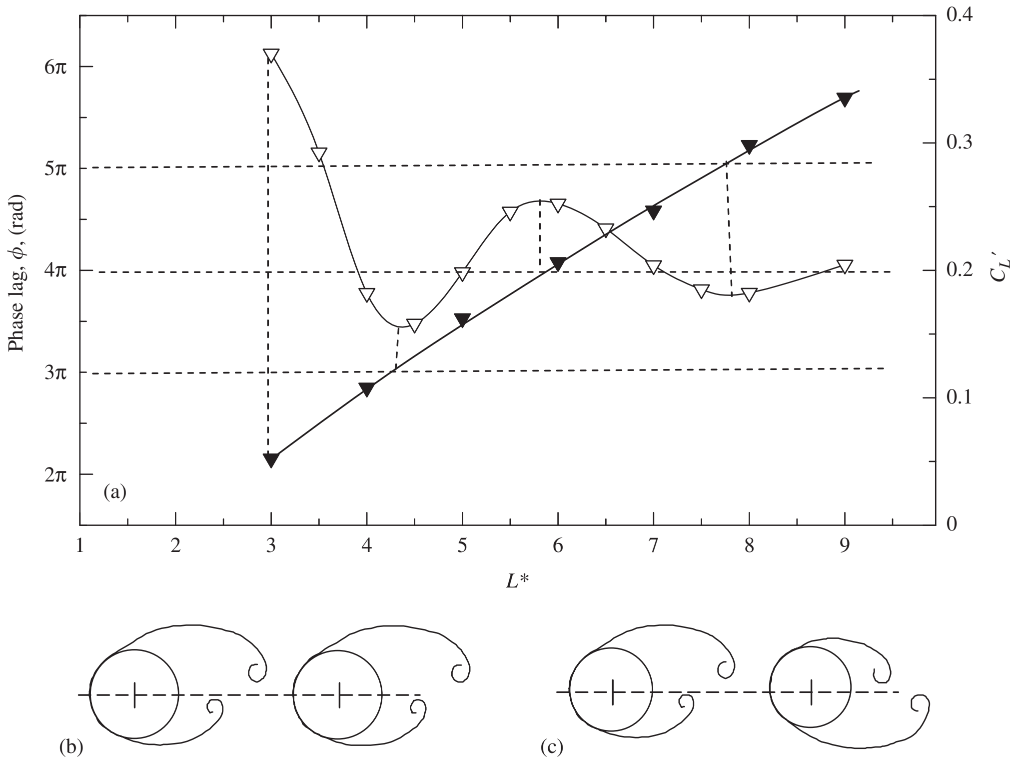

Fig. 4. (a) Effect of the phase lag ϕ (between fluctuating lift forces on the two cylinders) on C'_L of the upstream cylinder (Case 3); from Alam et al. (2006). (b) In-phase flow pattern at $L^* = 3$ and 5.75 that corresponds to a maximum C'_L. (c) Out-of-phase flow pattern at $L^* = 4.25$ and 7.75 that corresponds to a minimum C'_L. The overall uncertainties in C'_L and ϕ were $\pm 2\%$ and $\pm 3\%$, respectively.

minimum. Sakamoto et al. (1987) observed for Case 4 a higher C'_L at $L^* = 4$, where ϕ was 2π. The variation of C'_L with changing L^* appears sinusoidal, though its maximum or minimum value shrinks with increasing L^*, that is, the effect of ϕ on C'_L decreases. It may be concluded that ϕ is directly linked to C'_L.

For two tandem bluff bodies of any cross-section, there is an L_c^* which depends on the body cross-section (Alam and Sakamoto, 2005; Alam et al., 2006), Re (Xu and Zhou, 2004), and turbulent intensity (Sakamoto and Haniu, 1988). At L_c^*, ϕ is approximately 2π (Sakata and Kiya, 1983; Sakamoto et al., 1987; Alam et al., 2003, 2006), irrespective of bluff body shape. For example, in Cases 1–6, L_c^* was identified as 4, 3, 3, 4, 2.5, and 3.5, respectively, and the corresponding value of ϕ was about 2π (refer to Fig. 2).

3.2. Correlation between St, ϕ and L^*

The empirical correlation between L^* and ϕ could be obtained from curve-fits to data presented in Fig. 2 (see also the relevant literature for Cases 1–4), viz.

$$\phi = 0.50\pi L^* + 0.34\pi \quad (L^* \geqslant 4) \quad \text{[Case 1]}, \tag{2a}$$

$$\phi = 0.56\pi L^* + 0.46\pi \quad (L^* \geqslant 3) \quad \text{[Case 2]}, \tag{2b}$$

$$\phi = 0.58\pi L^* + 0.57\pi \quad (L^* \geqslant 3) \quad \text{[Case 3]}, \tag{2c}$$

$$\phi = 0.33\pi L^* + 0.65\pi \quad (L^* \geqslant 4) \quad \text{[Case 4]}, \tag{2d}$$

$$\phi = 0.30\pi L^* + 1.25\pi \quad (L^* \geqslant 2.5) \quad \text{[Case 5]}, \tag{2e}$$

$$\phi = 0.45\pi L^* + 0.42\pi \quad (L^* \geqslant 3.5) \quad \text{[Case 6]}. \tag{2f}$$

Note that in the literature L^* was defined as the gap spacing between the cylinders, as opposed to center-to-center spacing adopted presently. The above relationships are valid for $L^* \geqslant L_c^* = 4$, 3, 3, 4, 2.5, and 3.5 for Cases 1–6, respectively. Accordingly, the fluctuating lift on the upstream cylinder is very small. From Eq. (2), the slope $\mathrm{d}\phi/\mathrm{d}L^*$ is 0.50π, 0.56π, 0.58π, 0.33π, 0.30π and 0.45π for the six cases, respectively. If we divide these slopes by the corresponding St $= 0.2$, 0.225, 0.237, 0.13, 0.12 and 0.18, for Cases 1–6, respectively, we get $(\mathrm{d}\phi/\mathrm{d}L^*)/\mathrm{St} = 2.5\pi$, 2.48π, 2.45π, 2.53π, 2.5π and 2.45π, respectively. Thus, Eq. (2) could be rewritten as

$$\phi = 2.5\pi \mathrm{St} L^* + 0.34\pi \quad (L^* \geqslant 4) \quad [\text{Case 1}], \tag{3a}$$

$$\phi = 2.48\pi \mathrm{St} L^* + 0.46\pi \quad (L^* \geqslant 3) \quad [\text{Case 2}], \tag{3b}$$

$$\phi = 2.45\pi \mathrm{St} L^* + 0.57\pi \quad (L^* \geqslant 3) \quad [\text{Case 3}], \tag{3c}$$

$$\phi = 2.53\pi \mathrm{St} L^* + 0.65\pi \quad (L^* \geqslant 4) \quad [\text{Case 4}], \tag{3d}$$

$$\phi = 2.5\pi \mathrm{St} L^* + 1.25\pi \quad (L^* \geqslant 2.5) \quad [\text{Case 5}], \tag{3e}$$

$$\phi = 2.45\pi \mathrm{St} L^* + 0.42\pi \quad (L^* \geqslant 3.5) \quad [\text{Case 6}]. \tag{3f}$$

Note that $(\mathrm{d}\phi/\mathrm{d}L^*)/\mathrm{St}$ is almost constant, 2.48π, the maximum departure for individual cases being 2%. Therefore, a general equation for ϕ is proposed, viz.,

$$\phi = 2.48\pi \mathrm{St} L^* + C, \tag{4}$$

where C is a constant which could be obtained from the boundary conditions. As established earlier, $\phi = 2\pi$ at $L^* = L_c^*$; hence, $C = 2\pi - 2.48\pi \mathrm{St} L_c^*$, and Eq. (4) may be rewritten as

$$\phi = 2.48\pi \mathrm{St}(L^* - L_c^*) + 2\pi. \tag{5}$$

Eq. (5) specifies the relationship between ϕ, St and L^*, and could be used to determine ϕ and to estimate to a certain extent C'_L, provided that St and L_c^* are known.

4. Theoretical analysis

Presumably, vortex shedding from the downstream cylinder is triggered by vortices shed from the upstream cylinder. Then, ϕ should correspond to the time t required for a vortex to travel a distance L from the upstream cylinder to the downstream one. Let U_∞ represent the free-stream velocity, V_c the convective velocity of vortices, d the characteristic height of the upstream bluff body, f_s the frequency of vortex shedding and $T = 1/f_s$ the period of vortex shedding. In Fig. 5, let vortex A be displaced by an elemental length $\mathrm{d}x$ in time $\mathrm{d}t$. The corresponding increase is $\mathrm{d}V_c$ in V_c and $\mathrm{d}\phi$ in ϕ. Then, we get

$$\mathrm{d}x = \frac{V_c + (V_c + \mathrm{d}V_c)}{2}\,\mathrm{d}t, \tag{6}$$

where $V_c + (V_c + \mathrm{d}V_c)/2$ is the average velocity of vortex A in time $\mathrm{d}t$.

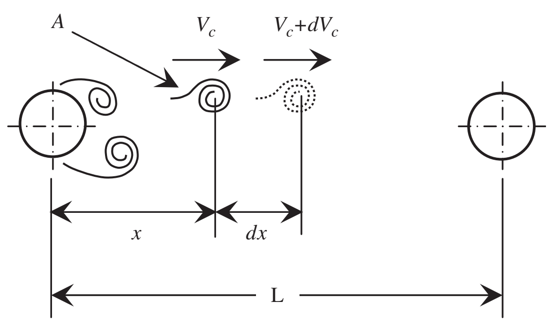

Fig. 5. Schematic showing convection of vortices.

Rearranging Eq. (6), we get

$$\mathrm{d}t = [2/(2V_c + \mathrm{d}V_c)]\mathrm{d}x. \tag{7}$$

Also, we know

$$\mathrm{d}\phi = (2\pi/T)\,\mathrm{d}t = 2\pi f_s\,\mathrm{d}t. \tag{8}$$

From Eqs. (7) and (8), we get

$$\mathrm{d}\phi = [4\pi f_s/(2V_c + \mathrm{d}V_c)]\mathrm{d}x. \tag{9}$$

Eq. (9) is a differential equation of ϕ in terms of f_s, x and V_c. Previous studies indicate that V_c is almost constant between $x^* \approx 3$ and 15, regardless of Re and the bluff body shape, as is evident in Fig. 6 and Table 1.

Based on Fig. 6 and Table 1, we choose $0.82U_\infty$, as a reference V_c. Given constant V_c, $\mathrm{d}V_c = 0$ and Eq. (9) reduces to

$$\mathrm{d}\phi = \frac{2\pi f_s}{V_c}\,\mathrm{d}x. \tag{10}$$

Integrating Eq. (10), we obtain

$$\phi = \frac{2\pi f_s x}{V_c} + C_1, \tag{11a}$$

where the integrating constant C_1 may be determined from a boundary condition. Replacing x by L, we obtain

$$\phi = \frac{2\pi f_s L}{V_c} + C_1. \tag{11b}$$

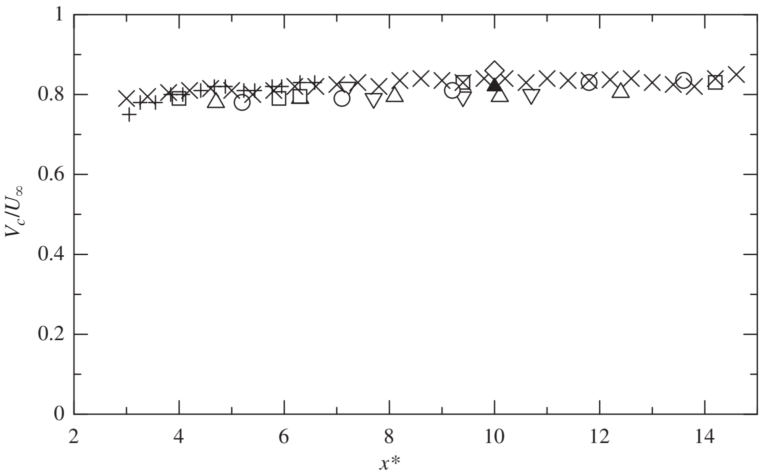

Fig. 6. Vortex convective velocity V_c in a circular cylinder wake: ($\times$) Re $= 3.9\times10^4$ (Tanaka and Murata, 1986); ($\triangle$) Re = 562 (Tyler, 1930); ($\square$), Re = 645 (Tyler, 1930); (∇) Re = 818 (Tyler, 1930); ($\bigcirc$) Re = 900 (Tyler, 1930); (+) Re $= 1.4\times10^5$ (Cantwell and Coles, 1983); ($\diamond$) Re $= 5.6\times10^3$ (Zhou and Antonia, 1992); and ($\blacktriangle$) Re = 60–100 (Paranthoen et al., 1999).

Table 1
Convective velocity V_c of vortices in the wake of various body-shapes

Research	Model	Re	V_c/U_∞
Fage and Johansen (1928)	Flat plate, |	Higher subcritical	0.77
Zdravkovich (1997, p. 375)	Circular cylinder, ●		0.80
	Wedge, ◀		0.82
	Ogival,		0.86
	Extended ogival,		0.81

At $\phi = 2\pi$, we have $L/d = L_c^*$. Then, we get $C_1 = 2\pi - 2\pi f_s L_c^* d/V_c$ and

$$\phi = (2\pi f_s d/V_c)(L^* - L_c^*) + 2\pi. \tag{11c}$$

Substituting $V_c = 0.82U_\infty$ in Eq. (11c) yields

$$\phi = 2.44\pi \frac{f_s d}{U_\infty}(L^* - L_c^*) + 2\pi = 2.44\pi \mathrm{St}(L^* - L_c^*) + 2\pi. \tag{12}$$

Eq. (12) is almost the same as Eq. (5), except for a small deviation (1.6%) in the slope. The deviation could be attributed to experimental uncertainly in measured ϕ and V_c. The equation suggests that ϕ is a function of St, L^* and L_c^*, and increases linearly with increasing L^*. Furthermore, $\mathrm{d}\phi/\mathrm{d}L^*$ is proportional to St. As St depends on the upstream cylinder shape, $\mathrm{d}\phi/\mathrm{d}L^*$ varies with the upstream cylinder shape.

It is worth commenting that V_c may vary appreciably for $x^* < 3$ [e.g., Cantwell and Coles (1983)], which raises the question on the effect of varying V_c on ϕ. As ϕ is estimated for $L^* > L_c^*$, this effect on ϕ should be independent of L^* for $L^* > L_c^*$, and is effectively incorporated in the determination of constant C_1.

5. Conclusions

The phase lag ϕ between vortex shedding from two tandem cylinders is connected to the forces on the cylinders. An empirical relationship between ϕ, St, L^* and L_c^* is derived from experimental data available in the literature. A general differential equation of ϕ, $\mathrm{d}\phi = [4\pi f_s/(2V_c + \mathrm{d}V_c)]\,\mathrm{d}x$, is developed theoretically, which yields $\phi = 2.44\pi\mathrm{St}(L_c - L_c^*) + 2\pi$ once applying the condition $\phi = 2\pi$ at $L_c = L_c^*$. This result agrees well with the empirical relation.

Acknowledgments

YZ wishes to acknowledge support given to him by the Research Grants Council of the Government of the HKSAR through Grants PolyU B-Q752.

References

Alam, M.M., Sakamoto, H., 2005. Investigation of Strouhal frequencies of two staggered bluff bodies and detection of multistable flow by wavelets. Journal of Fluids and Structures 20, 425–449.

Alam, M.M., Moriya, M., Takai, K., Sakamoto, H., 2003. Fluctuating fluid forces acting on two circular cylinders in a tandem arrangement at a subcritical Reynolds number. Journal of Wind Engineering and Industrial Aerodynamics 91, 139–154.

Alam, M.M., Sakamoto, H., Zhou, Y., 2006. Effect of a T-shaped plate on reduction in fluid forces acting on two tandem circular cylinders in a cross-flow. Journal of Wind Engineering & Industrial Aerodynamics 94, 525–551.

Cantwell, B.J., Coles, D., 1983. An experimental study of entrainment and transport in the turbulent near-wake of a circular cylinder. Journal of Fluid Mechanics 136, 321–374.

Fage, A., Johansen, F.C., 1928. The structure of vortex streets. Philosophical Magazine 7th Series 5, 417–441.

Papaioannou, G.V., Yue, D.K.P., Triantafyllou, M.S., Karniadakis, G.E., 2006. Three-dimensionality effects in flow around two tandem cylinders. Journal of Fluid Mechanics 558, 387–413.

Paranthoen, O., Browne, L.W.B., Masson, S.L., Dumouchel, F., Lecordier, J.C., 1999. Characteristics of the near wake of a cylinder at low Reynolds numbers. European Journal of Mechanics, B/Fluids 18, 659–674.

Sakamoto, H., Haniu, H., 1988. Effect of free stream turbulence on characteristics of fluctuating forces acting on two square prisms in tandem arrangement. ASME Journal of Fluids Engineering 110, 140–146.

Sakamoto, H., Oiwake, S., 1984. Fluctuating forces on a rectangular prism and a circular cylinder placed vertically in a turbulent boundary layer. ASME Journal of Fluids Engineering 106, 160–166.

Sakamoto, H., Haniu, H., Obata, Y., 1987. Fluctuating forces acting on two square prisms in a tandem arrangement. Journal of Wind Engineering & Industrial Aerodynamics 26, 85–103.

Sakamoto, H., Haniu, H., Obata, Y., Matubara, S., 1994. Optimum suppression of fluid forces acting on a circular cylinder and its effectiveness. JSME International Journal, Series B 37, 369–376.

Sakata, I., Kiya, M., 1983. Fluctuations acting on two circular cylinders in tandem arrangement. Transaction of JSME 49, 2618–2623 (in Japanese).

Tanaka, S., Murata, S., 1986. An investigation of the wake structure of a circular cylinder using a computer aided flow visualization. Bulletin of the JSME 29, 1446–1459.

Tyler, E., 1930. A hot-wire method for measurement of the distribution of vertices behind obstacles. Philosophical Magazine 7th Series 9, 1113–1130.

Williamson, C.H.K., 1989. Oblique and parallel modes of vortex shedding in the wake of a circular cylinder at low Reynolds number. Journal of Fluid Mechanics 206, 579–627.

Williamson, C.H.K., 1996. Vortex dynamics in the cylinder wake. Annual Review of Fluid Mechanics 28, 477–539.

Xu, G., Zhou, Y., 2004. Strouhal numbers in the wake of two inline cylinders. Experiments in Fluids 37, 248–256.

Zdravkovich, M.M., 1987. The effects of flow interference between two circular cylinders in various arrangements. Journal of Fluids and Structures 1, 239–261.

Zdravkovich, M. M., 1997. Flow Around Circular Cylinders, vol. 1. Fundamentals. Oxford Science Publications.

Zhou, Y., Antonia, R.A., 1992. Convection velocity measurements in a cylinder wake. Experiments in Fluids 13, 63–70.

Zhou, Y., Yiu, M.W., 2006. Flow structure, momentum and heat transport in a two-tandem-cylinder wake. Journal of Fluid Mechanics 548, 17–48.