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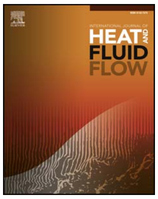

On forces and phase lags between vortex sheddings from three tandem cylinders

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ABSTRACT

This paper presents dependence of forces and flow structures on phase lags between vortex sheddings from three tandem cylinders. The flow around the three cylinders of an identical diameter D is numerically simulated at a Reynolds number $Re = 200$ for spacing ratios $L_1^* = L_1/D = 3.5$ - 5.25 and $= L_2/D = 3.6$ - 5.5, where L_1 is the center-to-center spacing between the upstream and middle cylinders, and L_2 is that between the middle and downstream cylinders. The variations in L_1^* and in these ranges correspond to the phase lags ϕ_1 (between the upstream and middle cylinders) and ϕ_2 (between the middle and downstream cylinders) both changing from inphase to antiphase. The flow around the cylinders is more sensitive to L_1^* than to , while both ϕ_1 and ϕ_2 have more influences on cylinder 1 than on the other two. An inphase condition ($\phi_1 = \phi_2 =$ inphase) corresponds to a high fluctuating lift and fluctuating shear-layer velocity but a small drag, Strouhal number, and time-mean shear-layer velocity for the upstream cylinder. On the other hand, an out-of-phase condition ($\phi_1 =$ inphase/antiphase and $\phi_2 =$ antiphase/inphase) complements the opposite, a small fluctuating lift and fluctuating shear-layer velocity.

1. Introduction

Because of its fundamental and practical importance, the flow around two circular cylinders in tandem arrangements has received a surge of attention in the literature. Vortex formation, forces, vibration, noise, and heat transfer were the focus of the most investigations in the literature (e.g., King and Johns, 1976; Zdravkovich and Pridden, 1977; Alam et al., 2003, 2007; Kitagawa and Ohta, 2008; Sumner, 2010; Kim et al., 2009; Liu et al., 2014). Particularly, dynamics and formation of vortices between two tandem cylinders are very complex, and the centre-to-centre spacing L between the cylinders is one of the key parameters, governing the flow structure around and mutual interference between the cylinders (Sumner, 2010; Alam and Meyer, 2011; Zhou and Alam, 2016). The flow interference between two cylinders is non-linear (Alam, 2016) and dependent on Reynolds number $Re = U_\infty D/\nu$ (Alam 2014), where D is the circular cylinder diameter or square cylinder width, U_∞ is the freestream velocity, and ν is the kinematic viscosity of the fluid.

There are several approaches for classifying the flow structures around two cylinders, based on spacing ratio $L^* = L/D$. For the flow around two tandem circular cylinders, Zdravkovich (1977) for $Re = 2.6 \times 10^3 - 2.1 \times 10^5$ classified the flow as overshoot regime ($L^* < 1.2$–1.8, depending on Re), where the free shear layers separating from the upstream cylinder overshoot the downstream cylinder and the flow in the gap between the cylinders is stagnant; reattachment regime (1.2–$1.8 < L^* < 3.4$–4.0), where the shear layers separating from the upstream cylinder reattach on the downstream cylinder; and coshedding regime ($L^* > 3.4$–4.0), where the shear layers shed vortices in the gap without reattaching on the downstream cylinder. The L^* separating the reattachment and coshedding regimes is known as the critical spacing L_c^*. Later, numerical simulations conducted by Mittal et al. (1997) shared the same information that vortices do not shed from the upstream cylinder for $L^* < L_c^*$ but do for $L^* > L_c^*$. Liu et al. (2014) conducted numerical simulations for the flow around two tandem circular cylinders at $Re = 200$ and identified similar flow classifications. Alam (2014) in wind tunnel experiments found that L_c^*

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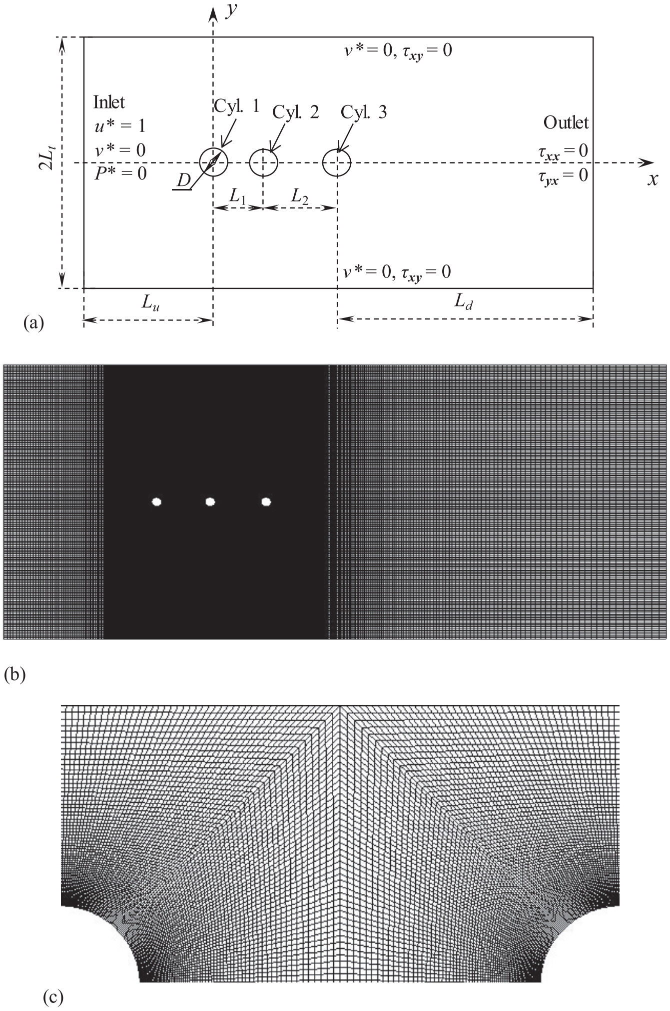

Fig. 1. (a) Schematic of the computational domain and boundary conditions, (b) structured grid distribution around three cylinders, and (c) zoom-in view of grids between two cylinders.

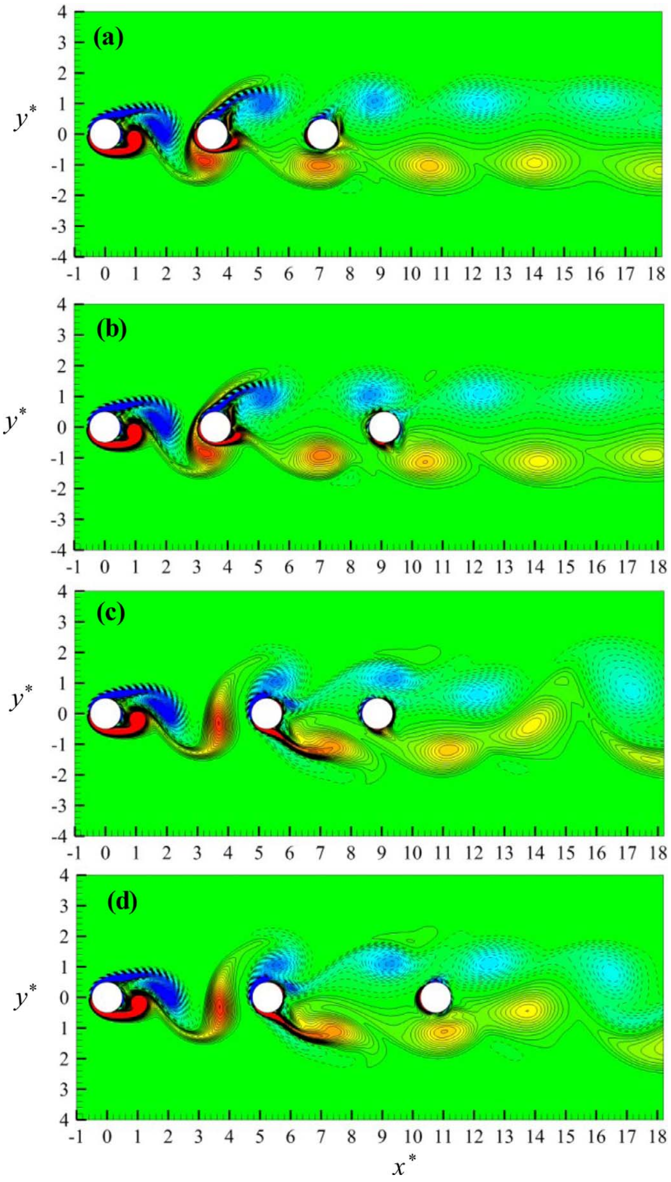

Fig. 2. Vorticity structures for (a) $L_1^* = 3.5$, $L_2^* = 3.6$, (b) $L_1^* = 3.5$, $L_2^* = 5.5$, (c) $L_1^* = 5.25$, $L_2^* = 3.6$, and (d) $L_1^* = 5.25$, $L_2^* = 5.5$. The instant of the snapshots corresponds to the minimum lift of cylinder 1.

is sensitive to *Re*, with $L_c^* = 3.7$, 3.6, 3.7 and 4.0 for $Re = 9.7 \times 10^3$, 1.6×10^4, 3.2×10^4 and 6.5×10^4, respectively. Ljungkrona and Sunden (1993) at $Re = 3.3 \times 10^3$–1.4×10^4, and $L^* = 1.25$ - 4.0 examined the flow structure and surface pressure around two tandem cylinders. They found that the variation of L_c^* with *Re* is connected to the dependence of the vortex formation length on *Re*. Wu et al. (1994) using flow visualization techniques examined flow structures around the tandem cylinders and outlined the important influence of *Re* on flow structures. They also estimated spanwise coherence from velocity and pressure fluctuations measured at a number of spanwise locations in the wakes. The spanwise coherence grows with decreasing L^*, becoming higher at $L^* < 3$ than that for a single cylinder. Wang et al. (2010) studied the flow around two tandem circular cylinders for $L^* = 1.0$ - 12.0 at $Re = 60$, 80 and 100 in a soap film tunnel. They progressively increased and decreased L^* and found that L_c^* is higher when the L^* is progressively increased than when it is progressively decreased.

Sakamoto and Haniu (1988) for two square tandem cylinders examined the effect of the freestream turbulence intensity T_u on L_c^*. They identified $L_c^* = 4.0$, 3.52 and 3.13 for $T_u = 1.4\%$, 2.4% and 4.8%, respectively, L_c^* shrinking with increasing T_u. Liu and Chen (2002) experimentally studied the flow around two tandem square cylinders for $L^* = 1.5$ - 9.0 and $Re = 2.0 \times 10^3$ - 1.6×10^4. A hysteresis in L_c^* is revealed when L^* is progressively increased or decreased. The hysteresis regime shifts towards a small L^* as *Re* is increased from 2.0×10^3 to 5.3×10^3 while it remains nearly unchanged at $Re = 5.3 \times 10^3$ - 1.6×10^4.

The effect of L^* on time-mean drag coefficient ($\overline{C}_D$) and Strouhal number (*St*) was investigated in the literature, whereas less attention has been devoted to investigating the fluctuating (r.m.s.) lift and drag coefficients C_{Lf} and C_{Df}. Mahir and Altca (2008) simulated the flow around two tandem cylinders and extracted $\overline{C}_D$, C_{Lf}, and *St* at $Re = 200$ for $L^* = 2.0$, 3.0, 4.0, 5.0, 7.0, and 10.0. The C_{Lf} of the upstream cylinder was obtained as 0.569, 0.517, 0.525 and 0.495 at $L^* = 4.0$, 5.0, 7.0, and 10.0, respectively. The C_{Lf} decreases between $L^* = 4.0$ and 5.0,