

## Cross-flow Past a Pair of Moderately Spaced Oscillating Circular Cylinders

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### ABSTRACT

Cross-flow past a pair of circular cylinders, with pitch ratio 2.5 and stagger angle  $21^\circ$ , and either one subject to forced harmonic oscillation in the transverse direction is investigated experimentally for  $525 \leq Re \leq 750$ . Flow-visualization and hot-film measurements of the wake formation region are reported. The wake undergoes considerable modification compared with the static case, and the manner in which the wake responds depends strongly on whether it is the upstream or downstream cylinder which is being oscillated. There are several distinct regions of synchronization between the dominant wake periodicities and the cylinder oscillation.

**KEY WORDS:** Staggered cylinder pair; cylinder oscillation; fundamental synchronization; superharmonic synchronization; flow patterns; flow visualization; wake periodicities.

### INTRODUCTION

Circular cylindrical structures subject to cross-flow, either alone or in groups, are very common features in various engineering applications. The flow around an isolated cylinder has been studied for years, and hence, is considered to be well understood. Although the flow around a small group of cylinders has not been extensively researched, it has received significant attention in recent times, and it has been shown that there are significant new complexities vis-à-vis the flow around an isolated cylinder. These include interactions between the individual shear layers, vortices and Kármán vortex streets.

The flow around a pair of staggered cylinders was first classified by Zdravkovich (1987), who, based on the position of the cylinders, identified three different flow regimes: (i) *no interference*, where the flow around each cylinder is effectively identical with that around a single cylinder; (ii) *wake interference*, where one cylinder is partially or completely submerged in the wake of the other; and (iii) *proximity interference*, where the cylinders are close to each other but neither is submerged in the wake of the other. However, Sumner et al. (2000) proposed that the flow around two cylinders is much more complex than this. They identified nine different flow patterns, although the patterns fall into three main categories, namely, *single bluff-body* flows,

*small-incidence-angle* flows and *large-incidence-angle* flows. They also suggested that the vortex shedding frequencies are associated more with the individual shear layers than with the individual cylinders.

Sumner and Richards (2003) investigated the steady lift and drag coefficients and Strouhal numbers in the subcritical Reynolds number range at  $P/D = 2.0$  and  $2.5$  with  $\alpha = 0 - 90^\circ$  ( $P$  = center-to-centre pitch ratio,  $D$  = cylinder diameter and  $\alpha$  = stagger angle). At  $P/D = 2.5$  and  $\alpha = 20^\circ$  they obtained two Strouhal numbers,  $St = 0.15$  and  $0.27$ . Later, Sumner et al. (2005) conducted an extensive investigation over a wider range of  $P/D$  and concluded that the higher of the two Strouhal numbers was associated with the upstream cylinder's shear layers, whereas the lower one originated from the downstream cylinder.

In a more recent study Alam and Sakamoto (2005) also obtained two Strouhal numbers in an investigation carried out at  $Re = 5.5 \times 10^4$  with  $P/D = 2.1 - 2.8$  and  $\alpha = 25^\circ$ . They employed standard Fourier and wavelet transform methods to analyze the fluctuating surface pressure acting on the cylinders, and concluded that the higher Strouhal number was generally associated with both the two shear layers shed from the upstream cylinder and the gap shear layer shed from the downstream cylinder, while the lower Strouhal number was associated with the outer shear layer shed by the downstream cylinder. From the wavelet analysis they also suggested that for periods of time the shear layers shed from either side of the upstream cylinder and from the gap side of the downstream cylinder would lock-in to those shed from the outer side of the downstream cylinder, yielding only the lower Strouhal number. For other periods of time, however, all the four shear layers would shed at the frequency associated with the outer shear layer of the upstream cylinder, yielding the higher Strouhal number. It should be noted that they did not conduct any visualization experiments to explain the flows or find any preference as to which of these flow patterns was dominant.

It is expected that the flow around a pair of cylinders will become more complex when one or both of the cylinders are subject to forced oscillation. For a single cylinder one of the most significant features caused by a forced oscillation is the fundamental lock-in, where the shedding frequency is synchronized with the excitation frequency,  $f_e$ . In addition to the fundamental lock-in, a number of sub- and