Vortex Shedding in a Tandem Circular Cylinder System With a Yawed Downstream Cylinder

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This investigation examines the flow produced by a tandem cylinder system with the downstream cylinder yawed to the mean flow direction. The yaw angle was varied from $\alpha = 90$ deg (two parallel tandem cylinders) to $\alpha = 60$ deg; this has the effect of varying the local spacing ratio between the cylinders. Fluctuating pressure and hot-wire measurements were used to determine the vortex-shedding frequencies and flow regimes produced by this previously uninvestigated flow. The results showed that the frequency and magnitude of the vortex shedding varies along the cylinder span depending on the local spacing ratio between the cylinders. In all cases the vortex-shedding frequency observed on the front cylinder had the same shedding frequency as the rear cylinder. In general, at small local spacing ratios the cylinders behaved as a single large body with the shear layers separating from the upstream cylinder and attaching on the downstream cylinder, this caused a correspondingly large, low frequency wake. At other positions where the local span of the tandem cylinder system was larger, small-scale vortices began to form in the gap between the cylinders, which in turn increased the vortex-shedding frequency. At the largest spacings, classical vortex shedding persisted in the gap formed between the cylinders, and both cylinders shed vortices as separate bodies with shedding frequencies typical of single cylinders. At certain local spacing ratios two distinct vortex-shedding frequencies occurred indicating that there was some overlap in these flow regimes.
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Introduction

One of the major sources associated with airframe noise are the landing gear arrangements that are deployed as the aircraft prepares to take-off or land. These are the times when the aircraft is the closest to the civilian populations, and the noise is of the greatest concern. Recent studies by Khorrami et al. [1] and Fitzpatrick [2] have attempted to understand the acoustic sources in landing gear by modeling the landing gear as tandem cylinders in cross flow. Other investigations have focused on single yawed cylinders [3–6], a configuration that closely resembles one strut of a multistrut landing gear. However, a more realistic configuration is a grouping of two tandem-yawed cylinders, where the upstream cylinder is maintained perpendicular to the mean flow and the downstream cylinder is angled, or yawed. The tandem-yawed cylinder system can be viewed as a tandem cylinder system where the local spacing ratio between the cylinders is being varied along the span of the cylinders. Figure 1 shows the arrangements examined in this investigation. The unsteady flow around this geometry is the focus of the current investigation.

Although a common arrangement in landing gear design, this particular geometry has not received any previous research interest; however, the case of two parallel tandem cylinders has been studied extensively [1,2,7–21]. The vortex shedding encountered in a tandem cylinder arrangement is normally characterized based upon the spacing ratio between the cylinders. Zdravkovich [9,10] and Igarashi [15] developed classifications for the vortex-shedding regimes as follows: for extremely small cylinder spaces $1 < S/D < 1.1-1.3$, no discernible vortex shedding occurs within the gap and the cylinders behave essentially as a single large bluff body. For intermediate spacing ratios $1.1-1.3 < S/D < 3.5-3.8$, the shear layers will separate from the upstream cylinder and reattach at different locations on the downstream cylinder. For larger spacings $3.8 < S/D < 5-6$, the cylinders begin to behave as separate entities with vortex shedding from each cylinder occurring and approaching the same frequency as the isolated cylinder case. Igarashi [15] notes that these spacings can depend somewhat on the Reynolds number of the flow if $\mathrm{Re} < 20{,}000$. Both Zdravkovich [11] and Sumner [22] provide excellent reviews of the flow around tandem cylinders.

Despite the breadth of information available on tandem cylinders in cross flow, relatively little is known about the effect of varying the yaw angle of one of the cylinders on the flow dynamics. However, a significant amount of research has been done on examining the flow from a lone yawed cylinder. For example, experiments conducted by Ramberg [3] and Snarski [4], as well as computational work by Marshall [5], showed that yawing the cylinder can cause the flow to become highly three dimensional, resulting in different shedding regimes for different spanwise locations. Recently, Hogan and Hall [6,23] used 16 simultaneous pressure measurements taken along the span of the single yawed cylinder to investigate the effect of yaw angle on the vortex shedding. They showed that the characteristics of the vortex shedding changed significantly along the span of the cylinder for yaw angles less than 70 deg and noted that yawing the cylinder causes the vortex shedding in the wake to become more disorderly. This was due to broadband three-dimensional turbulence developing on the upstream end of the cylinder which disrupts the once regular vortex shedding downstream, which was similar to Ramberg's [3] results at a much lower Reynolds number.

Ljungkrona and Sunden [18] performed streamwise flow visualization and Wu et al. [20] focused on examining the spanwise behavior of the flows over tandem cylinders with similar spacings to those examined here. The Reynolds numbers of both of those studies in the range of 10^3-10^4. Those studies employed blockage ratios of $4.5\%-6\%$, and length-to-diameter ratios of 16–24. Ljungkrona and Sunden [18] determined that the resulting flow field depended heavily on the spacing between the tubes, as well the effects of Reynolds number up to 10,000. For Reynolds numbers greater than 10,000 their pressure measurements showed that the shedding frequency was insensitive to Reynolds number

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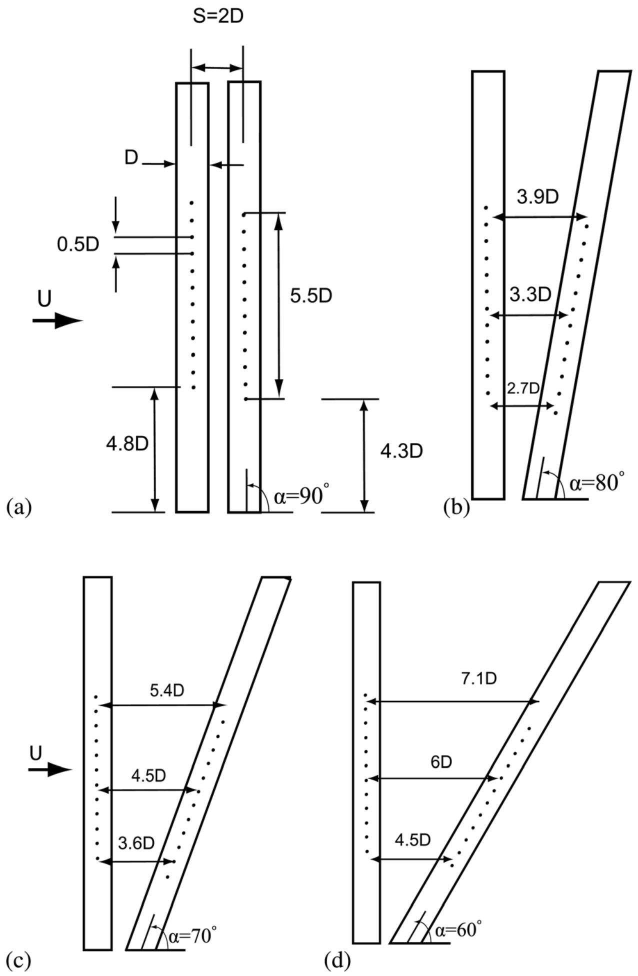

Fig. 1 Schematic of various yawed tandem cylinder systems with local spacing ratios, *S/D*, shown at the narrow, middle, and wide ends for (*a*) $\alpha = 90$ deg, (*b*) $\alpha = 80$ deg, (*c*) $\alpha = 70$ deg, and (*d*) $\alpha = 60$ deg

effects. Wu et al. [20] concluded that tandem cylinders showed higher spanwise coherence than single cylinders when the spacings between cylinders were small, $S/D < 3$.

Xu and Zhou [14] used a hot-wire anemometer to study the changes in dominant shedding frequencies measured in a tandem cylinder when the spacing between the cylinders was varied, over a variety of Reynolds numbers of $800-4.2 \times 10^4$. These are again similar to the Reynolds number investigated here. They examined two length-to-diameter ratios of 40 and 16 yielding two different blockage ratios of 2.5% and 6.7%, respectively. Xu and Zhou [14] concluded for $\mathrm{Re} > 20{,}000$ the shedding frequency from tandem cylinders no longer depended on Reynolds number, but was entirely governed by the spacings between the cylinders. This agreed with the earlier findings of Igarashi [15].

In the present experiment, the unsteady flow field in a yawed tandem cylinder system is examined using fluctuating pressure measurements taken on the surface of both the upstream and downstream cylinders simultaneously. These readings were used to determine the shedding frequencies from the cylinders. Using pressure taps mounted on the surface of the cylinders is a very common practice for examining vortex dynamics on tandem cylinders [8,17,18], as well as yawed cylinders [4,6]. Hot-wire probes were also used at select locations to confirm the microphone spectra results.

Experimental Setup

The experiments were conducted in a low-speed wind tunnel with a 0.58 m by 0.58 m square test section set up at the University of New Brunswick. The circular cylinders were 42.4 mm in diameter and made of aluminum. The velocity of the wind tunnel was set to $U_\infty = 20$ m/s corresponding to a Reynolds number based on the cylinder diameter of $56{,}000$. The cylinders were rigidly mounted to eliminate the possibility of any vibration and spanned the entire height wind tunnel, yielding a length-to-diameter ratio of 13.5 and a solid blockage ratio of only 7.4%. The yaw angle of the downstream cylinder α could be adjusted between $\alpha = 60$ deg and $\alpha = 90$ deg, while the upstream cylinder remained perpendicular to the mean flow.

The vortex-shedding frequency was ascertained using 12 simultaneous measurements of the fluctuating wall pressure on each cylinder and with a hot wire positioned behind or between the two cylinders to measure the unsteady wake. The microphones used in this study were Panasonic Electret Condenser Microphones, series WM-64PNT. Pressure measurements were made via a pin-hole configuration at the surface of each cylinder. The placement of the microphones is shown in Fig. 1. The microphones were connected to the pin holes via hypodermic tubing. The response of the mounted microphone system was determined to be flat from 20 to 1000 Hz. The 12 microphones were spaced $0.5D$ apart and spanned $5.5D$ along each cylinder, as shown in Fig. 1. The hot wire was placed $1D$ behind selected microphones. The experiment was repeated for six hot-wire locations, corresponding to the bottom, midspan, and top microphone positions on each cylinder. The microphone and hot-wire signals were sampled simultaneously at 10 kHz for 100 s using a 16-bit Microstar data acquisition system. The data was then partitioned into 100 blocks of 1 s duration, yielding an uncertainty in the magnitude of the spectra at each frequency of no greater than 20% at the 95% confidence interval.

Experimental Results

The first case investigated for this paper was that of a simple tandem arrangement where both cylinders were maintained parallel to one another ($\alpha = 90$ deg). The local center to center spacing of the cylinders remained constant at $S/D = 2$. In order to study the effects of the microphone azimuthal angle on the microphone and hot-wire readings, the experiment was repeated with the pressure taps on the downstream cylinder mounted at two azimuthal angles, $\gamma = 70$ deg and $\gamma = 90$ deg. The normalized power spectra for both the $\gamma = 90$ deg and the $\gamma = 70$ deg case are shown in Fig. 2. In all figures, the microphone spectra are normalized by the dynamic head of the mean flow squared q^2 and the hot-wire spectra are normalized by the upstream mean flow velocity squared U_∞^2.

Although there are some small changes in magnitude associated with the placement of the pressure tap, all pressure spectra indicates a single and identical dominant frequency component corresponding to a Strouhal number of 0.151 for the $\gamma = 90$ deg azimuthal case and 0.153 for $\gamma = 70$ deg. These values are in good agreement with Xu and Zhou [14] who reported a value of $\mathrm{St} = 0.15$ for a Reynolds number of $42{,}000$ for this spacing, and with the results of Ljungkrona et al. [17] who found a value of around $\mathrm{St} = 0.155$ for tandem cylinders with this spacing, but with lower a Reynolds number of $20{,}000$. The peaks are very sharp, indicating that the vortex shedding is strongly periodic, and associated with a single dominant frequency, as expected. The pressure readings from the downstream microphones showed much higher pressures on the downstream cylinders for all azimuthal angles examined. This is consistent with the findings of Arie et al. [8], who noted that pressure coefficient was much higher on the downstream cylinder of a tandem cylinder system. The spectra associated with the downstream cylinder are several orders of magnitude higher than those of the upstream cylinder, and as the dipole source at low Mach numbers is dominant, this likely indicates that the downstream cylinder would be the strongest contributor to noise in this tandem cylinder system.

Similar spectra for a tandem cylinder configuration with the downstream cylinder yawed to 80 deg are shown for an azimuthal angle of $\gamma = 90$ deg in Fig. 3. These results did show a slight

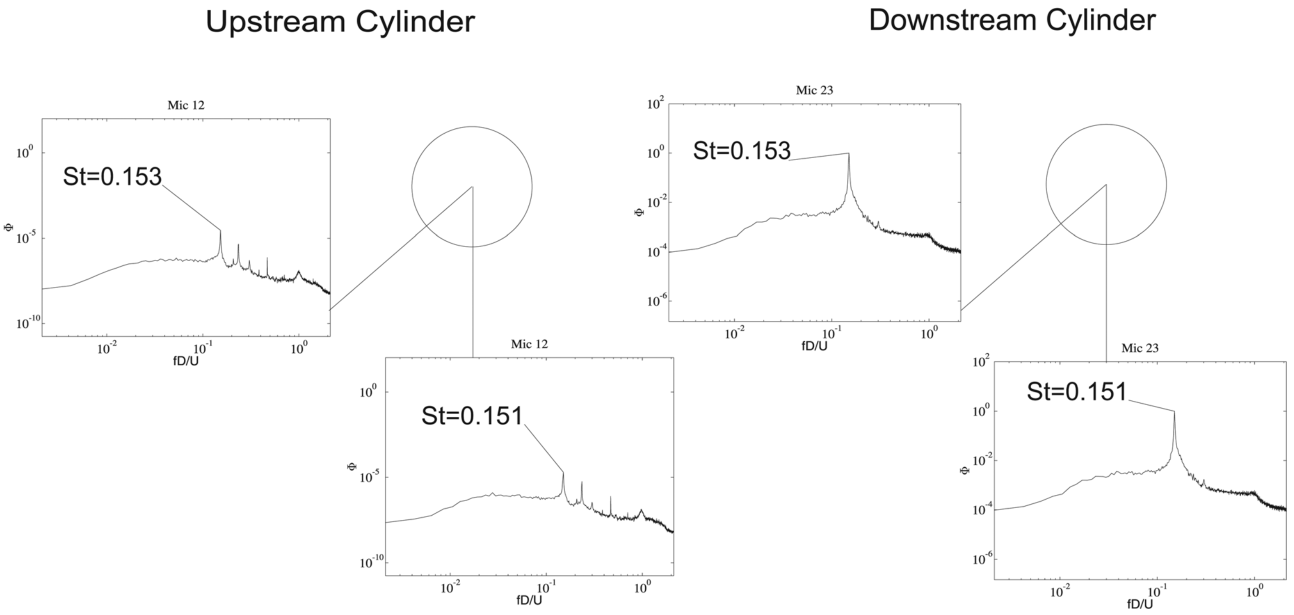

Fig. 2 Microphone power spectra normalized by dynamic head squared q^2 for $\alpha = 90$ deg for two azimuthal angles, $\gamma = 70$ deg and $\gamma = 90$ deg

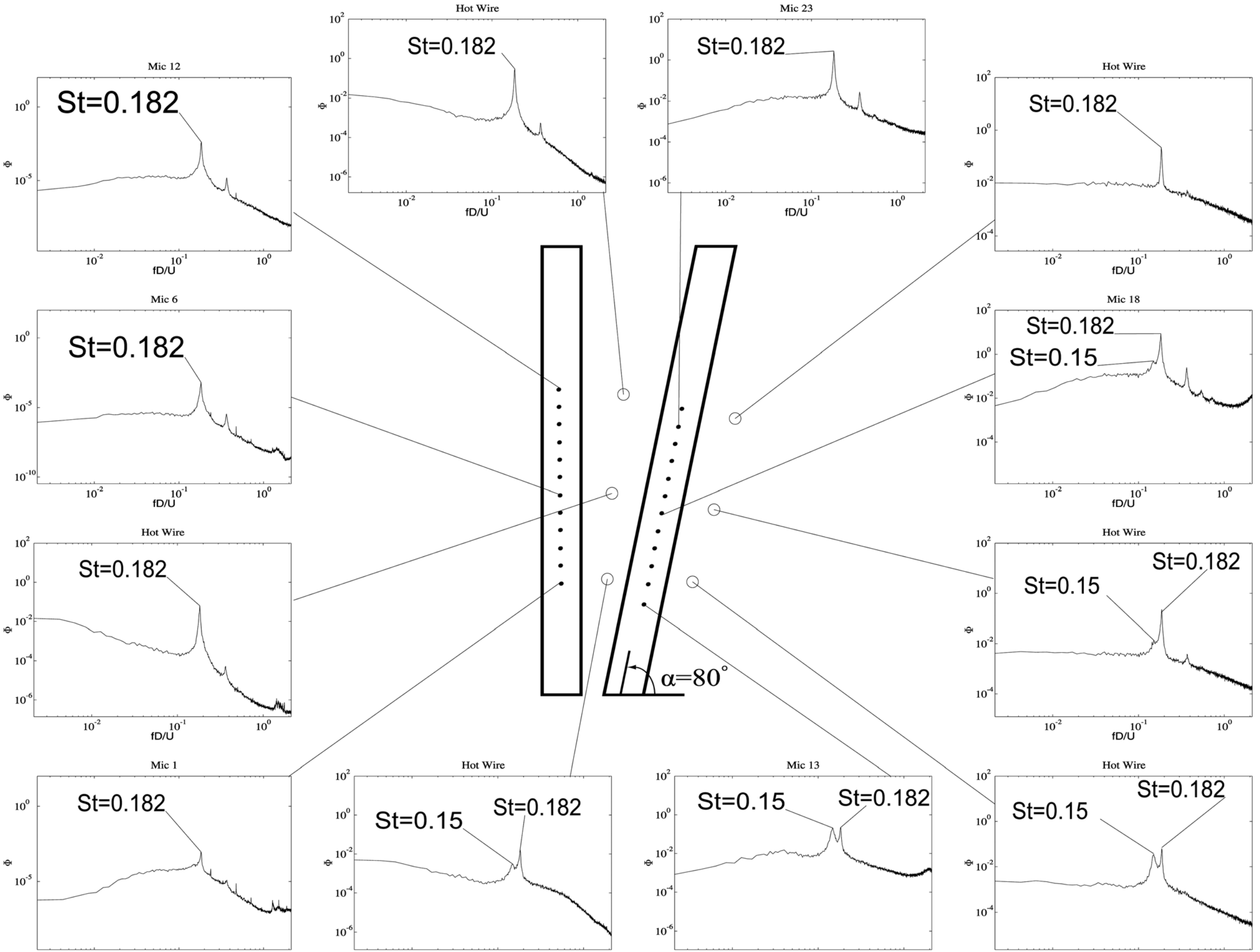

Fig. 3 Normalized power spectra at various spanwise locations for $\alpha = 80$ deg

sensitivity to azimuthal angle, primarily in the magnitude of the spectra. This was due to pressure taps on both cylinders being positioned at $\gamma = 70\,\text{deg}$, which was too far away from the separation and reattachment points to provide strong pressure fluctuations. However, the energy distribution with respect to frequency, f, did not change significantly. As shown, the local spacing ratio between the cylinders is no longer constant in the spanwise direction and varies along the cylinder span from $S/D = 2.7$ for the microphones mounted at narrow end increasing up to $S/D = 3.9$.

At the top half of the cylinder, where the local spacing ratio is the largest ($S/D = 3.9$), the pressure spectra obtained from the upstream cylinder have a single dominant peak associated with a Strouhal number of $\text{St} = 0.182$. The same frequencies persists in the wake and the gap hot wire at this location. Based upon the strong peak in the spectra, the Strouhal number and the local spacing ratio, it is likely that there is some form of vortex shedding occurring in the gap formed between the two cylinders and strong vortex shedding in the wake at this spanwise location. The magnitude of the spectra on the downstream cylinder are several orders of magnitudes higher than those found from the upstream spectra, indicating that the wake of the downstream cylinder shows a higher degree of vortex organization. When the local spacing ratio decreases down the cylinder span to about $S/D = 3.3$, a weak secondary peak at $\text{St} = 0.15$ begins to appear in the pressure spectra for the rear cylinder. The magnitude of the peak in the wake increases down the cylinder span until it becomes comparable to the peak at $\text{St} = 0.182$. The lower frequency peak is not observed at all in the microphone on the upstream cylinder, nor in the hot wire placed in the gap at this spanwise location, until the very lowest microphone positions. As this Strouhal number value was observed along the span for the yaw angle of $\alpha = 90\,\text{deg}$, it is likely that this frequency is associated with a similar flow regime; associated with the flow over the cylinders behaving like a body in the reattachment regime suggested by Zdravkovich [9,10], with the shear layers from the upstream cylinder attaching to the downstream cylinder. Yawing the rear cylinder causes the local pitch ratio to vary, which causes several of the established flow regimes to occur. Between these regimes an overlap region is formed where features of both regimes persist. Inspection of the time series associated with the velocity and pressure signals indicate that the flow is not bistable here and that both dominant frequencies persist. These regimes are formed because of the varying S/D ratios that cause the spacings to fall within different sections of tandem cylinder configurations.

Figure 4 shows the normalized power spectra taken from various microphones and the hot-wire readings just downstream of each microphone for $\alpha = 70\,\text{deg}$. At this yaw angle the rate of change of the local spacing ratio increase more rapidly, ranging from $S/D = 3.6$ at the lowest microphone position, to $S/D = 4.5$ in the middle portion of the cylinders, up to $S/D = 5.4$ for the top microphone position. For the microphones mounted near the base of the cylinder, the spectra plots showed a broad peak corresponding to a Strouhal number of $\text{St} = 0.189$. The peak in the spectra from both cylinders begins to narrow and shift to a higher Strouhal number as the local spacing ratio is increased from $S/D = 3.6$ up to $S/D = 4.5$, meaning the vortex shedding from the cylinders is becoming more organized and associated with a dominant frequency. The Strouhal number increases up to $\text{St} = 0.204$ which is approaching the accepted value for single cylinders of $\text{St} = 0.21$ [24]. The microphones mounted at the

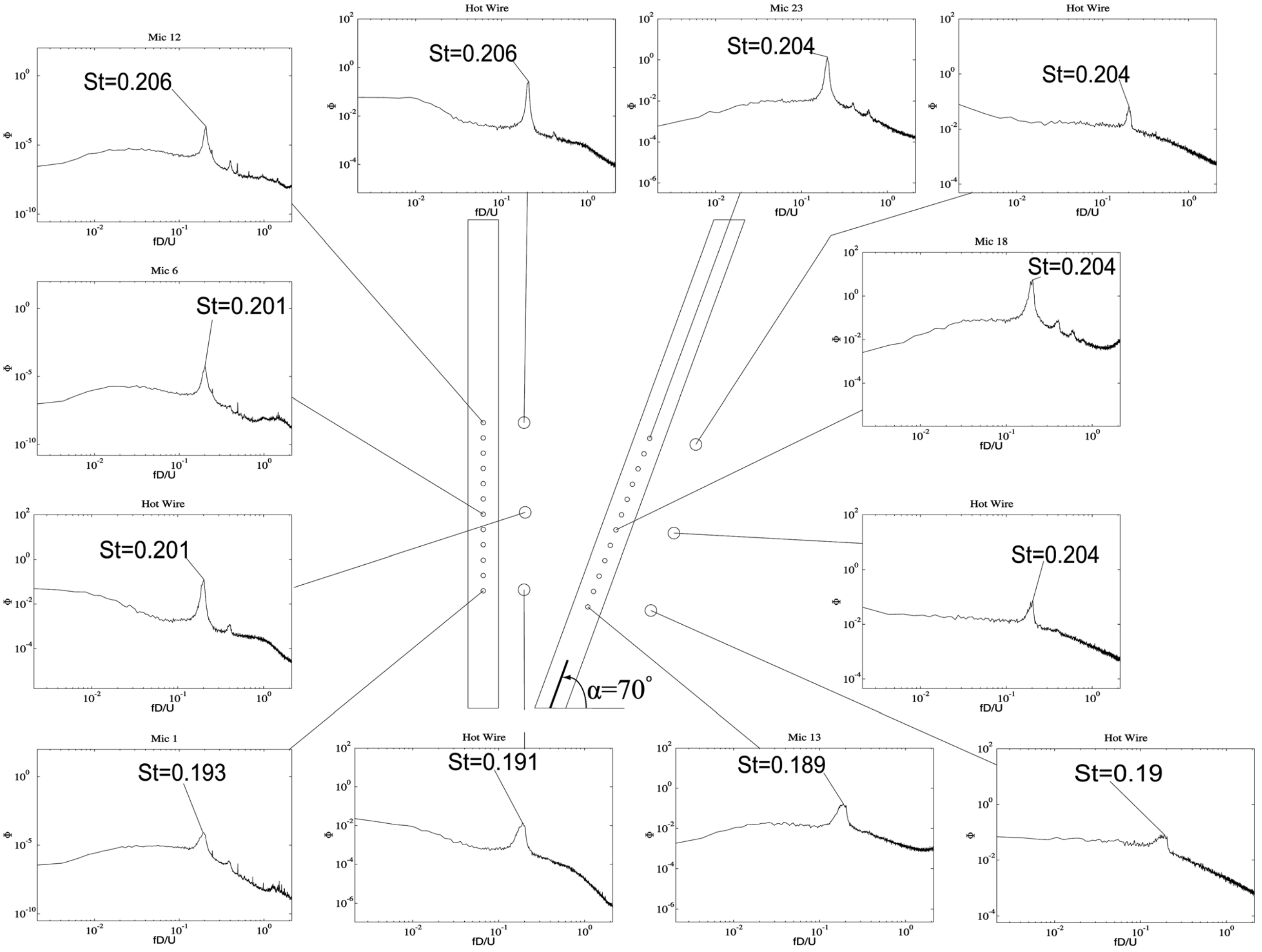

Fig. 4 Normalized power spectra at various spanwise locations for $\alpha = 70\,\text{deg}$

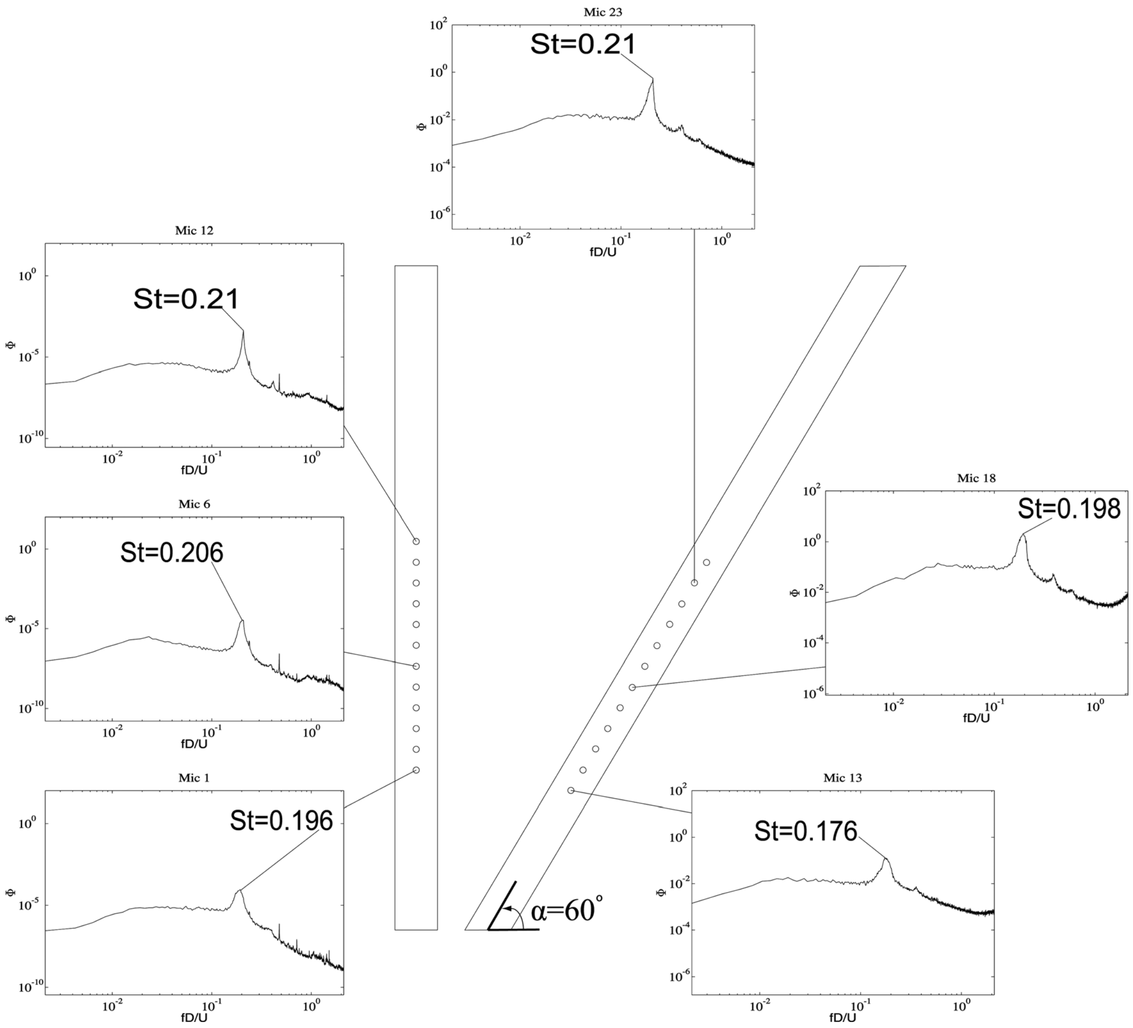

Fig. 5 Normalized power spectra at various spanwise locations for $\alpha = 60$ deg

highest vertical locations on each cylinder show even stronger peaks associated with a Strouhal number of $\mathrm{St} = 0.206$ which is consistent with the value reported for a single cylinder [24]. The local spacing ratio has increased to $S/D = 5.4$, which is within the spacing number range of $S/D = 5{-}6$ suggested by Zdravkovich [9,10], and likely indicates that there is distinct, classical vortex shedding within the gap. The magnitudes of the downstream spectra show significantly higher peaks than those of the upstream, meaning that even at this yaw angle, when most of the cylinders are spaced far enough apart to be essentially be considered separate bodies, the rear cylinder still shows the strongest degree of vortex organization. This is all the more surprising, when yawing a single cylinder to this angle causes the wake to become much more disorderly [3,4,6], again suggesting that the rear cylinder in this system would be the dominant acoustic source.

For the yaw angle set to 60 deg, shown in Fig. 5, the smallest local spacing ratios encountered in this geometry were found at $S/D = 4.5$, showing a broad peak around $\mathrm{St} = 0.176$. The peak narrows as the local spacing ratio increases to $S/D = 6$ along the midspan of the cylinder, and the Strouhal number increases up to $\mathrm{St} = 0.198$. Xu and Zhou [14] found similar Strouhal numbers when experimenting on tandem cylinders with similar spacing ratios and Reynolds numbers. As the local spacing continues to increase up to $S/D = 7.1$, the Strouhal number quickly approaches $\mathrm{St} = 0.21$, which is again consistent with the generally accepted value for single cylinders [24]. For this arrangement only microphone readings were taken, because the larger physical dimensions of the test model made it impractical to position the hot wire properly.

Discussion

An illustration summarizing the results and the proposed flow regimes is shown in Fig. 6, with the local spacings shown, and the proposed regimes outlined on the figure itself. The respective local S/D spacings are shown to the right of each figure. For the yaw angle set to $\alpha = 90$ deg, a local spacing ratio of $S/D = 2$ exists, and it is thought that the shear layers separate near the rear of the upstream cylinder and reattach near the rear of the downstream cylinder as observed by flow visualization of tandem cylinders by Xu and Zhou [14] and Ljungkrona and Sunden [18]. This behavior effectively causes a larger, low frequency wake than a single cylinder along with a Strouhal number of $\mathrm{St} = 0.151{-}0.153$.

As the yaw angle is decreased to $\alpha = 80$ deg, the flow becomes more complicated. The results indicate that are two frequencies encountered in this arrangement depending on the local cylinder spacing. For most spanwise locations for this configuration, the local spacing ratio $2.7 < S/D < 3.9$ is not large enough to allow for the formation of discrete vortices within the cylinder gap. This would account for the Strouhal number of $\mathrm{St} = 0.182$ along most of the span being smaller than the established value for classical vortex shedding from a single cylinder of $\mathrm{St} = 0.21$ [24]. Near the bottom of the cylinders, where the local spacing ratio is small, similar low frequency fluctuations are present as the tandem case ($\alpha = 90$ deg). An overlap region appears to persist between the

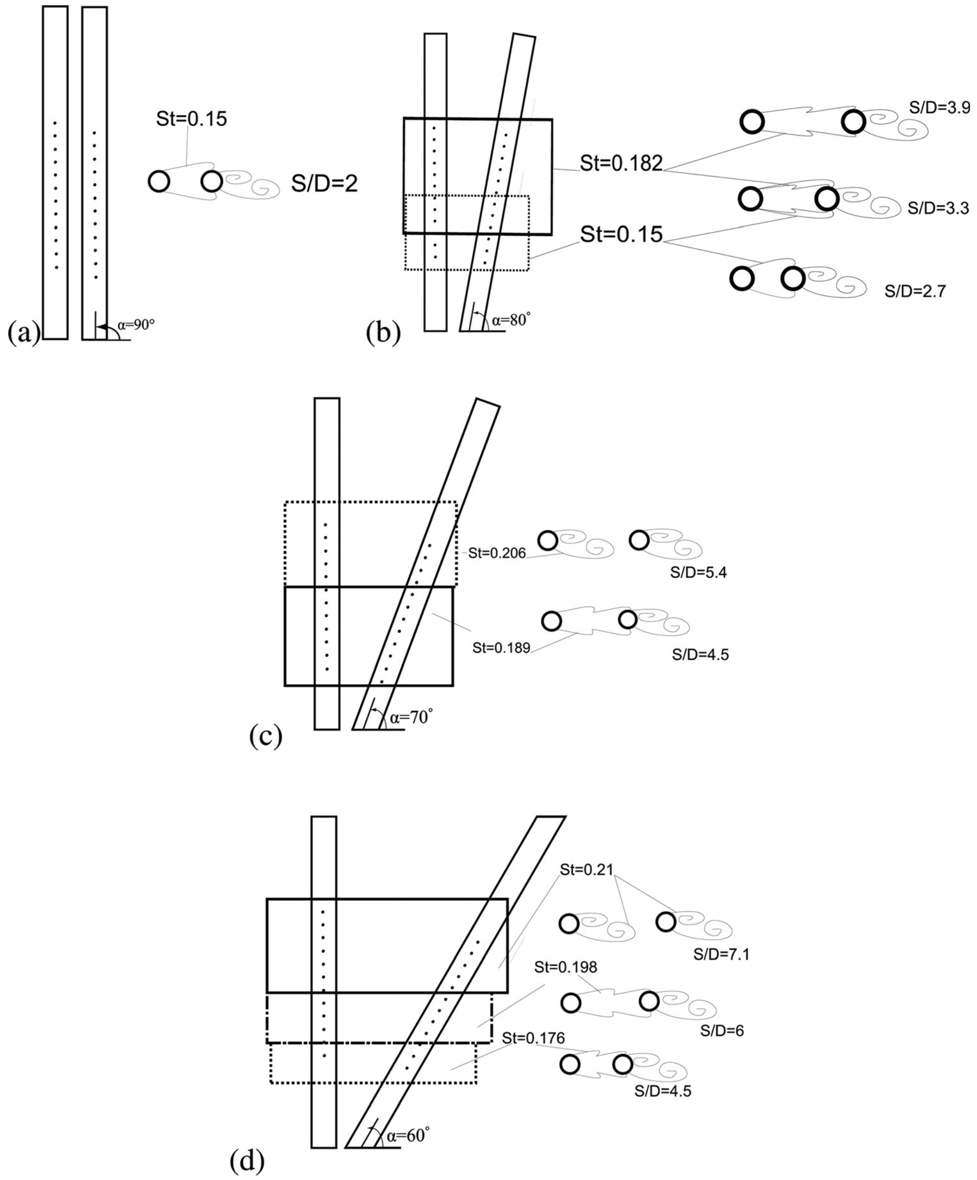

Fig. 6 Comparison of flow regimes for (*a*) $\alpha = 90$ deg, (*b*) $\alpha = 80$ deg, (*c*) $\alpha = 70$ deg, and (*d*) $\alpha = 60$ deg

two regions, where both modes of shedding are present. The results indicate that the flow is not bistable in the overlap region and both frequencies persist together.

A similar flow regime transition can be seen in the 70 deg yaw angle case as well. The lowest local spacing ratio of $S/D = 3.6$ shows a combination of flow regimes. Ranging from larger, lower frequency wakes, with Strouhal numbers around $\mathrm{St} = 0.189$ associated with shear-layer reattachment or the formation of smaller structures within the gap, to higher frequency regimes associated with discrete vortex shedding and Strouhal numbers up to $\mathrm{St} = 0.21$. The presence of multiple regimes results in a very broad peak in the spectra. As the spacing ratio moves through the intermediate regimes, with spacings around $S/D = 4.5$, the regime associated with smaller structures within the gap begins to dominate, and the Strouhal number shifts upwards to $\mathrm{St} = 0.204$, accompanied by a narrowing of the peak seen in the spectra. After the spacing ratio passes $S/D = 5.4$, distinct vortices are formed in both cylinder wakes, and the Strouhal number agrees with the established values for single cylinders $\mathrm{St} = 0.21$ [24]. Zdravkovich [9,10] noted that this spacing is sufficient for classical vortex streets to form within the gap resulting in a Strouhal number of $\mathrm{St} = 0.21$.

For the downstream cylinder yawed at 60 deg, the local spacing ratios changes very rapidly, increasing from $S/D = 4.5$ up to $S/D = 7.1$. Near the bottom microphone, the spacing ratio of $S/D = 4.5$ is not sufficient to allow discrete vortices to form in the gap, but the shear layers are beginning to roll up. This results in Strouhal numbers around $\mathrm{St} = 0.18$, a value approaching that for a single isolated cylinder, but still having some interference effects from the downstream cylinders. The midsection local spacing values are higher, resulting in smaller structures forming within the gap, with $\mathrm{St} = 0.198$. As this spacing ratio and larger, classical vortex streets are formed within the gap [9,10].

Unlike a traditional single yawed cylinder, the angled cylinder does not seem to support the development of high levels of turbulence, in this case the angled cylinder shows the highest degree of vortex organization. Earlier yawed cylinder works showed a breakdown of two-dimensional flow assumptions at large yaw angles [3,4,6], this arrangement saw strong piecewise two-dimensional behavior. Within certain local spacing ratio ranges, the flow can largely be treated as two dimensional. It is only within the overlap, or transition spacing regimes, where the flow becomes three dimensional.

Conclusion

The vortex shedding from a tandem cylinder system with the downstream cylinder yawed to the mean flow direction has been investigated for various yaw angles. It was observed that the vortex shedding can become significantly more complex due to the change in local spacing ratios associated with yawing the downstream cylinder. When the local spacings are kept small, the two cylinders behave as a single large body with a large wake resulting in low Strouhal numbers in the range of $\mathrm{St} = 0.15$ to 0.176. For the largest local spacing ratios, the two cylinders act essentially as separate entities, with Strouhal numbers identical to those of single cylinders, $\mathrm{St} = 0.21$ [15,24]. In the intermediate spacing ratios, there can be an overlap in the flow regimes from both the small and large spacings where both modes of vortex shedding are evident. In all cases, the downstream cylinder showed much higher magnitudes in the spectra, meaning the vortex shedding was more strongly organized in the wake of the downstream cylinder; this also suggests that at low Mach numbers that the rear cylinder should be the largest source of flow-generated noise. Particle image velocimetry (PIV) measurements are planned to fully understand the complex flow-structure interaction uncovered in this investigation and confirm the proposed flow regimes.

Acknowledgment

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Nomenclature

D = outer cylinder diameter, m
f = frequency, Hz
q = free stream dynamic head, $0.5\rho U_\infty^2$
S = local center to center spacing ratio, m
St = Strouhal number, $f_s D/U_\infty$
U_∞ = free stream velocity, m/s
α = yaw angle, deg
γ = azimuthal angle, deg
Φ = normalized power spectra
ρ = air density, $\mathrm{kg/m^3}$

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