Journal of Fluids and Structures 25 (2009) 461–478

JOURNAL OF FLUIDS AND STRUCTURES

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# Effect of acoustic resonance on the dynamic lift forces acting on two tandem cylinders in cross-flow☆

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Received 11 July 2008; accepted 7 August 2008
Available online 5 November 2008

**Abstract**

Direct measurements of the dynamic lift force acting on two tandem cylinders in cross-flow are performed in the presence and absence of acoustic resonance. The dynamic lift force is measured because it represents the integrated effect of the unsteady wake and therefore it is directly related to the dipole sound source generated by vortex shedding from the cylinder. Three spacing ratios inside the proximity interference region, $L/D = 1.75$, 2.5 and 3 are considered. During the tests, the first transverse acoustic mode of the duct housing the cylinders is self-excited. In the absence of acoustic resonance, the measured dynamic lift coefficients agree with those reported in the literature. When the acoustic resonance is initiated, a drastic increase in the dynamic lift coefficient is observed, especially for the downstream cylinder. This can be associated with abrupt changes in the phase between the lift forces and the acoustic pressure. The dynamic lift forces on both cylinders are also decomposed into in-phase and out-of-phase components, with respect to the resonant sound pressure. The lift force components for the downstream cylinder are found to be dominant. Moreover, the out-of-phase component of the lift force on the downstream cylinder is found to become negative over two different ranges of flow velocity and to virtually vanish between these two ranges. Acoustic resonance of the first mode is therefore excited over two ranges of flow velocity separated by a non-resonant range near the velocity of frequency coincidence. It is therefore concluded that the occurrence of acoustic resonance is controlled by the out-of-phase lift component of the downstream cylinder, whereas the effect of the in-phase lift component is confined to causing small changes in the acoustic resonance frequency.


*Keywords:* Tandem cylinders; Acoustic resonance; Dynamic lift force; Flow-acoustic interaction

## 1. Introduction

Vortex shedding from cylinders in cross-flow generates sound, which reflects back from surrounding surfaces and creates a feedback cycle that enhances the shedding process. As a result, if the flow excitation energy is sufficiently high to overcome the acoustic damping of the system, an intense acoustic resonance could be excited. Flow-excited acoustic

☆An earlier version of this paper was presented in the 7th FSI, AE and FIV+N Symposium, held within the 2006 PV and P Conference in Vancouver, BC, Canada.

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0889-9746/$ - see front matter 
doi:10.1016/j.jfluidstructs.2008.08.007

**Nomenclature**

| | |
|---|---|
| $c$ | speed of sound |
| $C_L$ | root mean square coefficient of fluctuating lift force on the cylinder |
| $C_{dh}$ | out-of-phase component of the lift force |
| $C_{mh}$ | in-phase component of the lift force |
| $D$ | cylinder diameter |
| $F_{\text{rms}}$ | root mean square amplitude of the fluctuating lift force acting on the cylinder |
| $f_a$ | frequency of the lowest acoustic resonance mode of the test section |
| $f_v$ | vortex-shedding frequency |
| $H$ | height of the duct |
| $\ell$ | cylinder length |
| $L$ | centre-to-centre distance between the cylinders |
| $M$ | Mach number |
| $P_{\text{rms}}$ | root mean square amplitude of acoustic pressure. |
| $P^*$ | normalised sound pressure |
| Re | Reynolds number |
| St | Strouhal number of vortex shedding |
| $t$ | time |
| $U$ | upstream flow velocity |
| $U_r$ | reduced velocity |
| $\rho$ | air density |
| $\omega$ | circular frequency of the vortex shedding |
| $\lambda$ | wavelength of the acoustic wave |
| $\theta$ | pressure tap orientation angle with respect to the front stagnation point |
| $\phi_{\text{Lift}}$ | phase shift between the dynamic lift force and the acoustic pressure on the top wall |

resonance of ducts containing clusters of bluff bodies is a design concern in many engineering applications, because it can generate acute noise problems or cause structural damage due to acoustic fatigue.

While the ability of sound to modulate, and essentially ''lock-in'', the process of vortex shedding is relatively well understood for the case of a single cylinder (Blevins, 1985), the details of the coupling and energy transfer mechanisms between the flow field and the resonant sound field are not yet fully understood, especially for multiple bluff bodies. Recent studies by Mohany and Ziada (2005) have shown that the aeroacoustic response of two tandem cylinders in cross-flow can be considerably different from that of a single cylinder under similar flow conditions. In the tandem cylinders case, strong resonance of a given acoustic mode occurs over two different ranges of flow velocity, which is in contrast with the single cylinder case for which the resonance occurs over a single velocity range. The flow mechanisms causing this difference are not fully understood.

Vortex shedding from cylinders in cross-flow generates a sound field similar to that radiated from a dipole sound source. The strength of this dipole source and its associated sound field can be expressed in terms of the hydrodynamic fluid forces, i.e., lift and drag forces, acting on the cylinder (Phillips, 1956). However, experimental measurements have shown that the fluctuating drag force for a cylinder in cross-flow is approximately 5–10% of the fluctuating lift force, (Anagnostopoulos, 2002). Therefore, the aeroacoustic source that excites the resonance can be represented by a dipole source, which is equivalent to the integrated effect of the vortex-shedding process. Since this dipole is dominant in the lift direction, measurement of the dynamic lift force and its phase with respect to the sound field is crucial to understanding the coupling and energy transfer mechanisms between the flow field and the sound field. This information is also needed to assess the increase in the dynamic fluid loading on the cylinder due to the excitation of acoustic resonance. Clearly, the acoustic resonance is found to enhance the vortex-shedding process and thereby to increase the dynamic lift coefficient. This enhancement in the lift coefficient due to acoustic resonance has never been investigated to date.

Direct measurement of the dynamic lift force in the case of *self-excited acoustic resonance* is by no means a straightforward task. The difficulty in performing these measurements is due to the fact that acoustic resonance in gas flows generally occurs at high frequencies and therefore requires a *stiff* force measuring set-up with a mechanical natural frequency that is sufficiently higher than the acoustic resonance frequency. However, the dynamic forces acting on cylinders in gas flows are rather small and require sensitive transducers for accurate measurements. The force measuring set-up must therefore meet these contradictory requirements, i.e. it must be sufficiently stiff but also sensitive enough to measure small forces accurately.

The effect of self-excited acoustic resonance on the vortex-shedding process and the hydrodynamic forces acting on the cylinder could be studied, to various degrees, in two ways: either by oscillating the flow around a fixed bluff body using loudspeakers (Hall et al., 2003), or by forcing the body itself to oscillate in cross-flow (Sarpkaya, 2004). The excitation mechanism however becomes more apparent by investigating the case of self-excited resonance (Mohany and Ziada, 2005b). Moreover, in many studies, only *indirect* measurements of the dynamic lift forces have been performed; see for example (Bishop and Hassan, 1964 and Carberry et al., 2001). Various techniques used in the literature to measure the fluctuating lift acting on a stationary circular cylinder in cross-flow have been discussed in some details by Norberg (2003).

For the case of a forced oscillating cylinder in cross-flow, a sudden change in both the amplitude and the phase of the lift force near the frequency coincidence has been observed by many researchers; just to name a few, see Bishop and Hassan (1964), Govardhan and Williamson (2000) and Carberry et al. (2001). This behaviour suggests that there is a significant change in the timing of vortex shedding and thereby positive energy could be transferred from the flow field to the cylinder oscillation.

Sarpkaya (1978) investigated the hydrodynamic fluid forces exerted on an oscillating cylinder in cross-flow. He presented the lift force coefficient as a function of the Fourier averaged values of both the inertia coefficient, which is the lift component in-phase with the cylinder displacement, and the drag coefficient, which is the lift component out-of-phase with the cylinder displacement, i.e. opposite to the cylinder velocity. He observed that the inertia force coefficient became negative at a reduced velocity of 5.2, while the drag force coefficient became negative at a reduced velocity of 4.8. Moreover, the range over which the drag coefficient was negative increased as the oscillation amplitudes decreased. Sarpkaya (1978) concluded that the cylinder oscillations were amplified when the drag coefficient was negative and thereby had the same sign as the cylinder velocity. At this phase condition, positive energy is transferred from the fluid to the cylinder.

In the present paper, direct measurement of the dynamic lift force is performed during the acoustic resonance for two tandem cylinders in cross-flow. The force transducer used in this study was developed and validated by Mohany and Ziada (2007). The spacing ratios between the cylinders are within the proximity interference region ($L/D = 1.75$, 2.5 and 3, where $L$ is centre-to-centre distance between the cylinders and $D$ is the cylinder diameter). The lift force coefficient is measured and analysed using an approach similar to that used for forced oscillating cylinders in cross-flow. In particular, it is decomposed into in-phase and out-of-phase components, with respect to the resonant sound pressure, to explore the mechanism of energy transfer between the flow and the sound field. These coefficients are also compared with those for the case of a single cylinder in cross-flow.

## 2. Experimental set-up

### 2.1. Test set-up

The experiments were performed in an open-loop wind tunnel at Reynolds number from $1.5 \times 10^4$ to about $1.35 \times 10^5$. The test-section was made of 25.4 mm thick clear acrylic walls to facilitate a flow visualisation study in the future. It had a cross-section of 76.2 mm in width by 254 mm in height. These were carefully selected to ensure coincidence between the frequency of the first acoustic resonance mode in the transverse direction ($f_a = c/2H \approx 688$ Hz) and the frequency of vortex shedding from the cylinder. As shown in Fig. 1, the first acoustic mode consists of a half-wavelength standing wave between the top and bottom walls of the test section, and its frequency, $f_a$, can be estimated from the height of the test section, $H$, and the speed of sound, $c$, at room temperature ($f_a = c/2H \approx 688$ Hz). For all cylinders used to measure the lift force, the wind tunnel blockage ratio was less than 8%. The cylinders were made of aluminium and they were machined to ensure that they all have qualitatively similar surface roughness. The flow velocity inside the test section was calibrated by means of a pitot tube and a pressure transducer. Several preliminary measurements of the flow velocity at different transverse (and streamwise) positions showed that the velocity profile was uniform and within $\pm 2\%$ of the mean velocity. The streamwise turbulence intensity was also measured and found to be less than 2%. The aspect ratio of the cylinders used to measure the lift force varied between 4.1 and 6. This relatively short cylinder length was necessary to ensure coincidence of the vortex-shedding frequency with the acoustic mode frequency at sufficiently high flow velocities. As discussed by several authors, for example by Fitzpatrick (1986), Blevins and Bressler (1993) and Mohany and Ziada (2006), frequency coincidence at a sufficiently high-flow velocity is a necessary condition for the generation of self-excited acoustic resonances. This necessity was confirmed by means of preliminary tests with smaller diameter cylinders to increase the aspect ratio. In these preliminary tests, self-excited acoustic resonances could not be generated within the tested range of flow velocity.

As seen in Fig. 1, the fluctuating pressure on the top wall of the duct was measured using a $\frac{1}{4}$ inch condenser microphone, which was flush mounted on the test-section top wall at the location of the maximum acoustic pressure. This location was determined in preceding experiments. Further details of the experimental set-up can be found in Mohany and Ziada (2005).

### 2.2. Force transducer

The dynamic lift forces were measured simultaneously with the fluctuating pressure, in the presence and absence of the acoustic resonance, using the force measuring device shown in Fig. 2. This measuring device, which is referred to

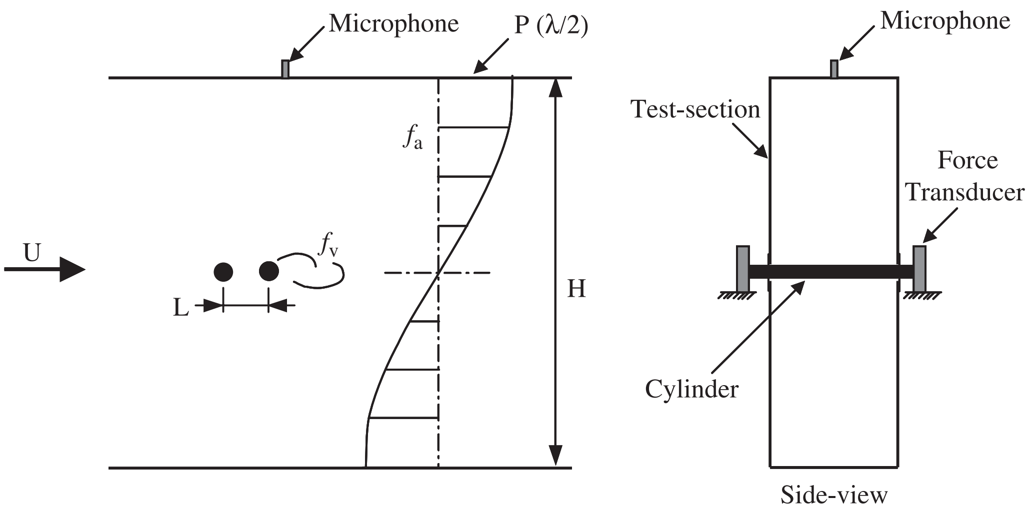


Fig. 1. Schematic drawing of the test-section showing the position of the microphone, the acoustic pressure distribution of the first acoustic mode $P(\lambda/2)$, and the method of supporting the cylinder.

hereafter as the force transducer, incorporated a PCB piezoelectric load cell. The force transducer was carefully designed to meet challenging demands. For example, its resonance frequency ($\approx$1300 Hz) must be sufficiently higher than the maximum vortex-shedding frequency of interest to ensure flat amplitude response and negligible phase shift over the frequency range of interest. This feature requires a stiff system. At the same time, it must be sufficiently sensitive to measure accurately the relatively small aerodynamic lift force, especially in the absence of acoustic resonance. This feature requires a soft system. It was also desired to maximise the stiffness of the transducer in the drag direction, in comparison to that in the lift direction, to minimise the imprint of the drag force in the transducer signal. These requirements were adequately met by the design shown in Fig. 2. In this design, the cylinder was attached to cantilevered beam springs. PCB force sensors were then used to preload the cantilevered beam springs. In this way, the fluctuating forces on the cylinder are directly sensed by the PCB transducers at both ends of the cylinder. Further details about the transducer can be found in Mohany and Ziada (2007).

The force transducer was fixed to a rigid frame outside the test section by means of a leveling base, as shown in Fig. 1. This levelling base was necessary to centre the cylinder within the holes in the test-section sidewalls. The rigid frame was isolated from the ground to eliminate transmission of vibration to the transducer. The mass of the cylinder was selected such that the lowest mechanical resonance frequency of the force measuring system is about twice the acoustic resonance frequency of the first transverse mode.

As shown in Fig. 1, the cylinder protruded through two holes on the test section sidewalls and was attached, outside the test section, to a force transducer at each end. The gap between the hole and the cylinder was 0.5 mm. As seen in Fig. 2, a soft rubber gasket was used to prevent air leakage into the test-section. The gasket did not influence either the acoustic resonance or the mechanical response of the transducer.

### 2.3. Pressure taps

A 0.5 mm hole was drilled at the midspan of a cylinder, 19 mm in diameter, to measure the fluctuating surface pressure on the cylinder. This hole is connected to a microphone via a 7.15 mm hole that was drilled through the cylinder, as shown in Fig. 3. This configuration resulted in a negligible phase lag between the pressure fluctuations on the cylinder surface and that received by the microphone. As seen in Fig. 1, the cylinder is positioned at the middle of the duct, which is the location of an acoustic pressure node for the first acoustic mode. Therefore, the pressure tap is mainly measuring the fluctuating pressure on the cylinder surface caused by the vortex shedding and not that generated by the pressure of the resonant acoustic mode.

A PCI-4452 four channel, 16 bit data acquisition system combined with a LabView program were used for spectral analysis, coherence and phase measurements. Each spectrum was obtained by averaging 100 samples. The acoustic pressure and the lift force data were collected simultaneously at a sampling rate of 4096 Hz.

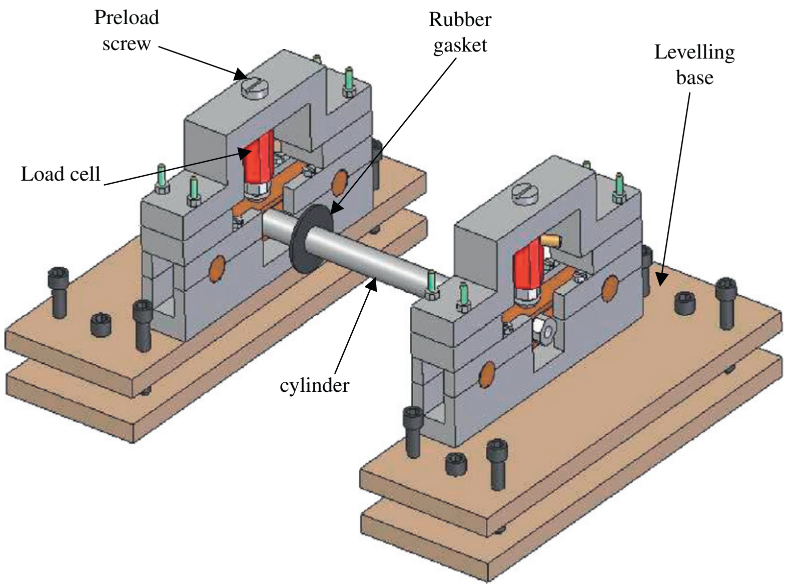


Fig. 2. Isometric view of the force transducer.

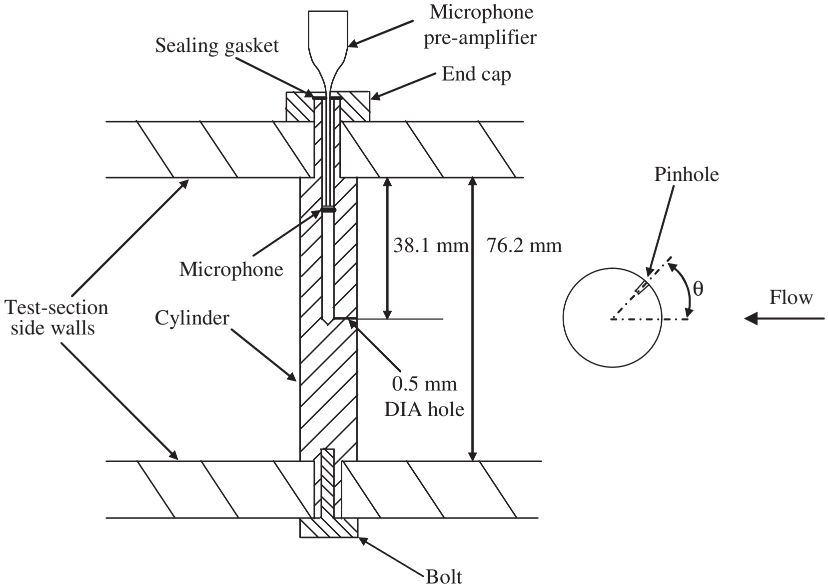


Fig. 3. Schematic drawing of the pressure tap configuration.

## 3. Lift force coefficient

Fig. 4 shows typical pressure and force spectra taken at a flow velocity before the onset of acoustic resonance for the case of two tandem cylinders with a spacing ratio $L/D = 2.5$. The fluctuating pressure is measured on the top wall of the duct and the lift force is measured on the downstream cylinder. A well-defined spectral peak corresponding to the

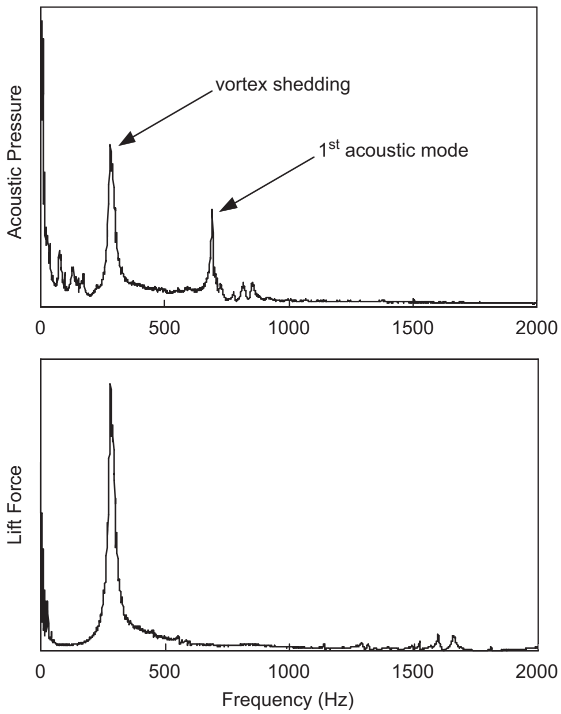


Fig. 4. Typical spectra of pressure on the top wall and force on the downstream cylinder taken before the onset of acoustic resonance, $L/D = 2.5$, $D = 15.2\,\text{mm}$, $U = 29.4\,\text{m/s}$ ($U_r = 2.8$).

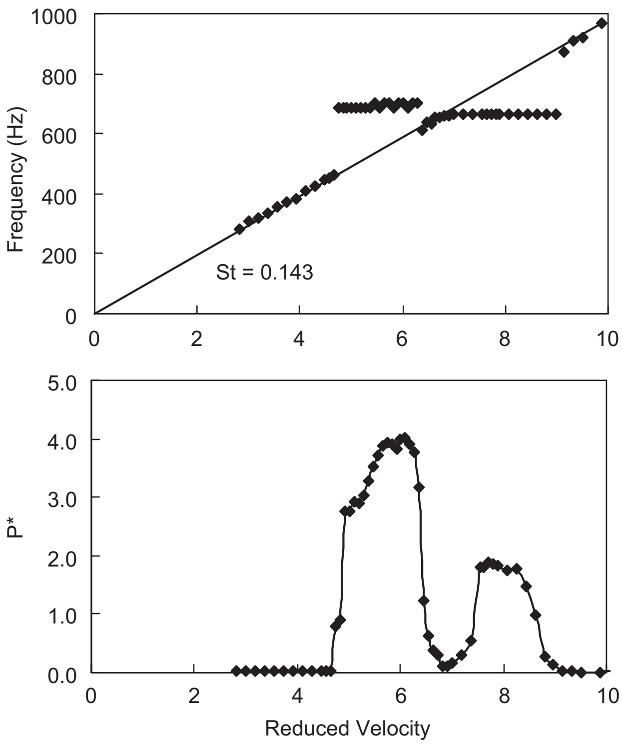


Fig. 5. Frequency and amplitude of pressure fluctuation on the test section top wall at the frequency of vortex shedding. $L/D = 2.5$, $D = 15.2\,\text{mm}$.

vortex-shedding frequency can be observed in both the pressure and the force spectra. The higher component in the pressure spectrum near 688 Hz is the first acoustic mode of the duct housing the cylinders. Fig. 5 shows the frequency of vortex shedding as well as the normalised amplitude of fluctuating pressure, $P^*$, at the vortex-shedding frequency, as functions of the reduced velocity, $U_r$. These measurements were taken by the microphone on the top wall of the test-section. The reduced velocity is based on the frequency of the lowest acoustic mode of the test section, $f_a$, as illustrated in Eq. (1), and the fluctuating, or sound pressure, $P_{\mathrm{rms}}$, is normalised by the dynamic head, $\frac{1}{2}\rho U^2$, multiplied by the Mach number, $M$, as shown in Eq. (2):

$$U_r = \frac{U}{f_a \times D}, \tag{1}$$

$$P^* = \frac{P_{\mathrm{rms}}}{(1/2)\rho U^2 M}, \tag{2}$$

where $U$ is the upstream flow velocity, $D$ is the cylinder diameter, $P_{\mathrm{rms}}$ is the root mean square of the acoustic pressure and $\rho$ is the air density. The average Strouhal number of vortex shedding during off-resonance condition is approximately $\mathrm{St} = fD/U = 0.143$, which is slightly lower than the value of 0.15 reported by Igarashi (1981). This small difference may be caused by differences in the test conditions such as the Reynolds number, turbulence intensity or aspect ratio. Note that the Reynolds number and turbulence intensity are higher in the present study than in the experiments of Igarashi (1981).

As can be seen in Fig. 5, the first acoustic mode of the duct near 688 Hz is excited over two ranges of flow velocity. Mohany and Ziada (2005) reported that the second resonance range, which extends between $U_r = 7$ and 9 and is

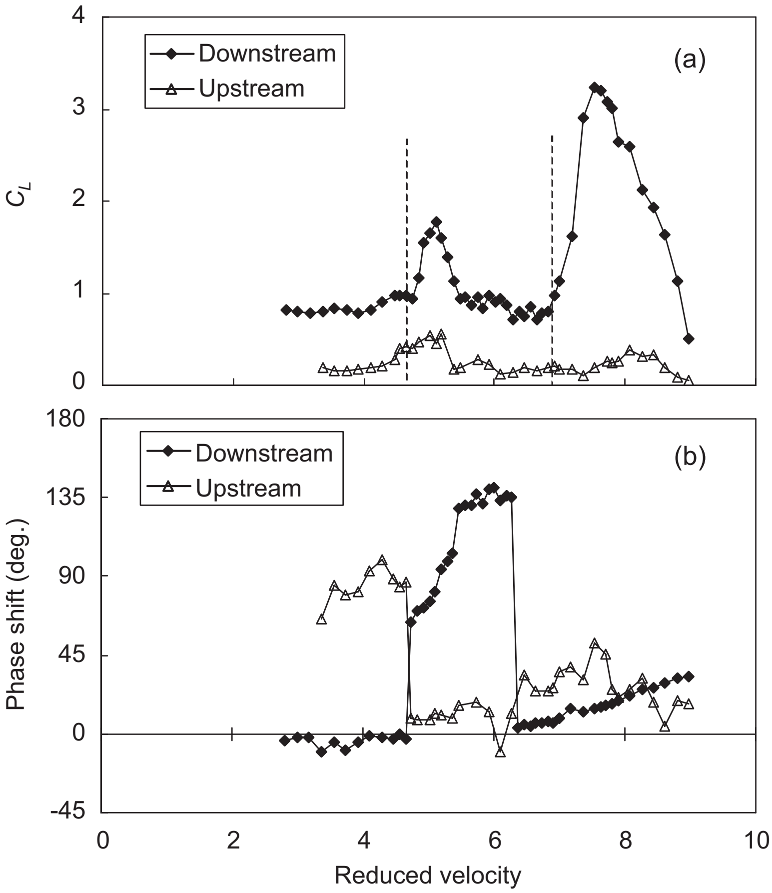


Fig. 6. Results of force measurements for $L/D = 2.5$: (a) dynamic lift coefficient at the frequency of vortex shedding and (b) its phase with respect to the acoustic pressure measured on the top wall. $D = 15.2$ mm. The dashed lines indicate the onset of acoustic resonance and the beginning of lock-in ranges.

referred to hereafter as the coincidence resonance, is excited by vortex shedding in the wake of the downstream cylinder. On the other hand, the instability of the shear layers in the gap between the cylinders has been suggested to be the excitation source causing the pre-coincidence resonance range, which extends from $U_r = 4.5$ to 6.5. In the following, the nature of the dynamic lift coefficient acting on the cylinders is investigated in some detail. First, its amplitude and phase, with respect to the resonant sound field, is addressed. Thereafter, an approach similar to that used by Sarpkaya (1978, 2004), for the case of forced oscillating cylinders, is used to decompose the lift force into the in-phase and out-of-phase components, with respect to the resonant sound field.

The dynamic lift coefficients at the frequency of vortex shedding are shown in Fig. 6(a) for $L/D = 2.5$. These lift coefficients are obtained by summing the lift forces measured at both ends of the cylinder. It is noteworthy that during acoustic resonance, the dynamic lift forces measured at each end of the cylinder were found to be in-phase and to have identical amplitudes. However, at the off-resonance conditions, the dynamic lift forces measured at each end of the cylinder had a small phase shift of about 5° and their amplitudes were within 6% of the mean value. These small differences in amplitude and phase are due to the three-dimensional effects of the flow before the onset of acoustic resonance. Upon the onset of resonance however, these differences vanish, indicating that the flow in the near-wake during acoustic resonance is strongly correlated in the spanwise direction and its integrated effect can be approximated by that of a two-dimensional flow. It should be noted that at high flow velocities, when the vortex-shedding frequency substantially exceeded the frequency of the first acoustic mode of the duct, the lift force signals were observed to become affected by the mechanical resonance frequency of the force transducer. Therefore, the results presented in Fig. 6

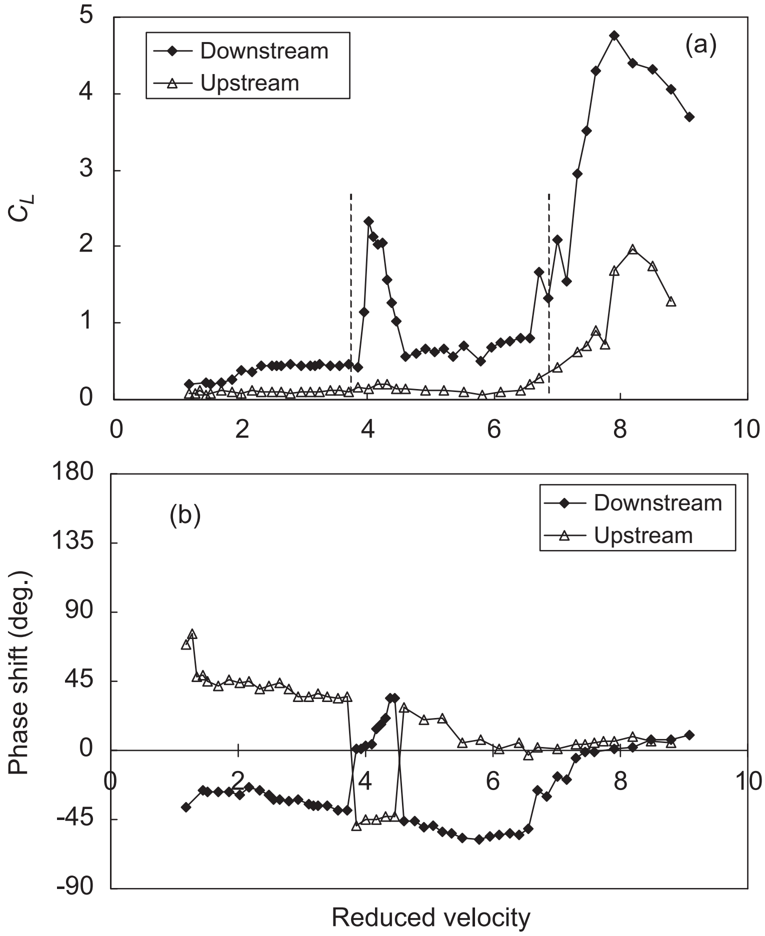


Fig. 7. Results of force measurements for $L/D = 1.75$: (a) dynamic lift coefficient at the frequency of vortex shedding and (b) its phase with respect to the acoustic pressure measured on the top wall. $D = 18.4$ mm. The dashed lines correspond to the onset of acoustic resonances and the beginning of the lock-in ranges.

correspond to those which were not influenced by the transducer response. The lift coefficient amplitude, $C_L$, is calculated from the root-mean-square amplitude of the lift force, $F_{\mathrm{rms}}$, using the following equation:

$$C_L = \frac{F_{\mathrm{rms}}}{(1/2)\rho U^2 D\ell}, \tag{3}$$

where $F_{\mathrm{rms}}$ is the sum of the dynamic lift forces at both ends of the cylinder, and $\ell$ is the cylinder length.

As can be seen in Fig. 6(a), the dynamic lift force coefficient for the downstream cylinder is much higher than that for the upstream cylinder, which agrees with the findings of other studies, such as Alam et al. (2003). Outside the resonance range, the dynamic lift force for the downstream cylinder varies between 0.78 and 0.93 for a reduced velocity range of $U_r = 2.8$–$4.5$, which corresponds to a range of Reynolds number between $4.5 \times 10^4$ and $7.3 \times 10^4$. On the other hand, the dynamic lift coefficient for the upstream cylinder, in the absence of resonance, varies between 0.15 and 0.21 for the same range of Reynolds number. These results agree with those of Alam et al. (2003), reporting values of 0.85 for the downstream cylinder and about 0.07 for the upstream cylinder for the same spacing ratio. Again, the small differences from the present results are due to different experimental conditions, such as Reynolds number and turbulence intensity.

Similar trends were observed for $L/D = 1.75$ and 3, as shown in Figs. 7(a) and 8(a). In the case with $L/D = 3$, the dynamic lift coefficient for the downstream cylinder varies between 0.65 and 0.88 for a range of Reynolds number between $3.7 \times 10^4$ and $6 \times 10^4$, while that for the upstream cylinder varies between 0.18 and 0.39. These values are smaller, especially for the upstream cylinder, in the small spacing case with $L/D = 1.75$, as can be seen in Fig. 7(a).

During acoustic resonance a drastic increase in the dynamic lift coefficient is observed. For the case with $L/D = 2.5$, the lift coefficient in the coincidence resonance range approaches a value of 3.2 for the downstream cylinder, which is about 4 times higher than that recorded at off-resonance conditions. Moreover, during the pre-coincidence resonance range for $L/D = 3$, the lift coefficient approaches a value of 4.2 for the downstream cylinder, which is about 6 times higher than that measured at off-resonance conditions. Similar effects were observed also for the case with small

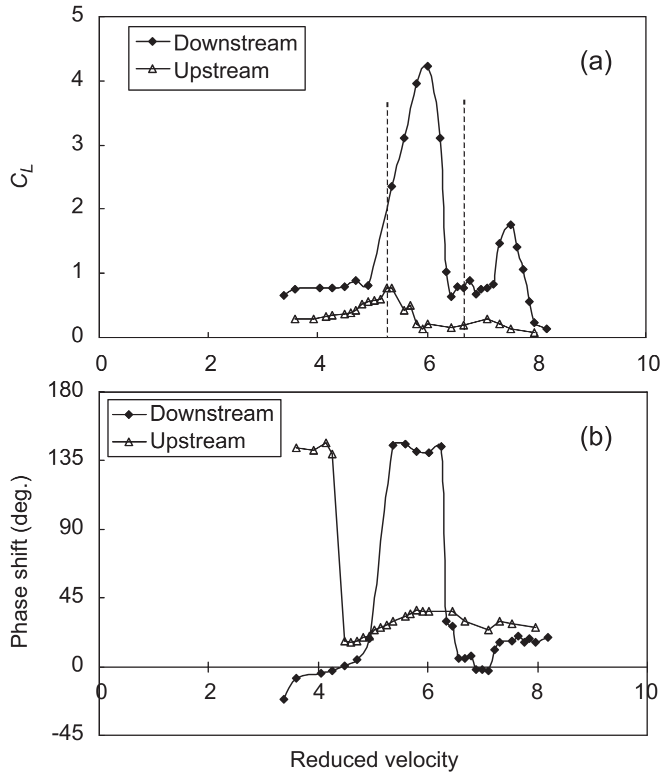


Fig. 8. Results of force measurements for $L/D = 3$: (a) dynamic lift coefficient at the frequency of vortex shedding and (b) its phase with respect to the acoustic pressure measured on the top wall. $D = 12.7$ mm. The dashed lines indicate the onset of acoustic resonance and the beginning of the lock-in ranges.

spacing, as can be seen in Fig. 7(a). These results demonstrate that acoustic resonances are not only a source of noise, but they could also cause structural fatigue damage due to excessive dynamic loading. It should be noted also that the dynamic lift coefficient data shown in Figs. 6–8 include the effect of acoustic resonance and therefore they provide design engineers with a means to assess the impact of acoustic resonance on the dynamic loading of structural components in industrial applications. To the authors' knowledge, these are the first lift coefficient data which include the effect of acoustic resonance.

## 4. Phase characteristics

The phase difference between the dynamic lift force and the acoustic pressure acting on the top wall of the test section is shown in Figs. 6(b), 7(b) and 8(b) for $L/D = 2.5$, 1.75 and 3, respectively. It is important at this point to mention that a positive signal from the microphone corresponds to a positive acoustic pressure, and a positive signal from the force transducer corresponds to an upward lift force. Note that the microphone is positioned on the top wall of the tunnel, as shown in Fig. 1. The location of the reference microphone was determined from preliminary measurements of the acoustic pressure distribution in the streamwise direction; see Mohany and Ziada (2005) for more details. However, in order to properly assess the phase characteristics of the dynamic lift forces with respect to the resonant sound field, it is important to examine if there is any change in the phase angle of the acoustic pressure with the microphone streamwise location or with the flow velocity. Therefore, two additional microphones were positioned upstream and downstream of the reference microphone, and the phase angles between the microphones were measured as functions of the reduced velocity. The upstream and the downstream microphones were located at $2.34D$ and $1.74D$, respectively, apart from the reference microphone. As can be seen in Fig. 9, the phase difference between the three microphones is small and does not change much with the flow velocity. It remains within $\pm 10^\circ$ when the acoustic resonance is strongly excited. These values are relatively small and are expected to have insignificant effect on the measurements of the phase angle between the lift force and the acoustic pressure.

As can be seen in Figs. 6(b) and 8(b), the phase difference between the dynamic lift force and the acoustic pressure shows similar trends for $L/D = 2.5$ and 3, although the absolute values may differ slightly. Before the onset of the pre-coincidence resonance, there is a substantial phase difference between the lift forces on the upstream and downstream cylinders. Note that the lift on the upstream cylinder is leading that on the downstream one. *At the onset of the pre-coincidence resonance*, the phases of the lift forces on both cylinders, with respect to the acoustic pressure, exhibit sudden jumps, which reverses their relative phase and the lift on the upstream cylinder becomes lagging the downstream one. However, the lift forces still maintain a substantial phase difference between each other, which varies between $90^\circ$ and $130^\circ$ over the pre-coincidence resonance range. *At the end of the pre-coincidence resonance*, near $U_r = 6.3$ for both $L/D = 2.5$ and 3, the lift of the downstream cylinder undergoes a sudden phase jump of about $130^\circ$, but that of the upstream cylinder does not show any sudden changes in its phase. For $L/D = 1.75$, Fig. 7(b) shows similar phase characteristics, except that the lift of the upstream cylinder also undergoes a frequency jump at the end of the pre-coincidence resonance to maintain a phase difference between the two cylinders similar to that observed before the onset of resonance. This behaviour, which is distinct from the other two cases with larger spacing ratios, is logical because the pre-coincidence resonance subsides at a reduced velocity of $U_r = 4.5$, which is substantially smaller than the corresponding value in the other two cases, $U_r = 6.3$. Interestingly, as the reduced velocity is increased to about $U_r = 6.3$, Fig. 7(b) shows that the phase between the lift forces starts to decrease gradually until the lift forces become virtually in-phase during the coincidence resonance, which is similar to the other cases of larger spacing ratios. Thus, for the three tested cases, the lift forces on both cylinders become virtually in-phase with each other at the onset of the coincidence resonance near $U_r = 7$. In fact, comparing Figs. 6–8 near $U_r = 7$ shows that the phase difference between the lift forces is almost identical for the three cases. It is interesting to note that the lift forces of both cylinders show only minor phase jumps, if any at all, at the onset of the coincidence resonance. They remain virtually in-phase with each other and show only slight variations with the reduced velocity until the end of the coincidence resonance range. At the end of this range, no phase jumps are observed either.

## 5. Pressure fluctuation on cylinder surface

Several authors in previous studies used an indirect method to evaluate the lift force and its phase by measuring the fluctuating surface pressure around the circumference of the cylinder through a pinhole arrangement. Since this technique provides only a point measurement, exhaustive measurements for many angles around the cylinder

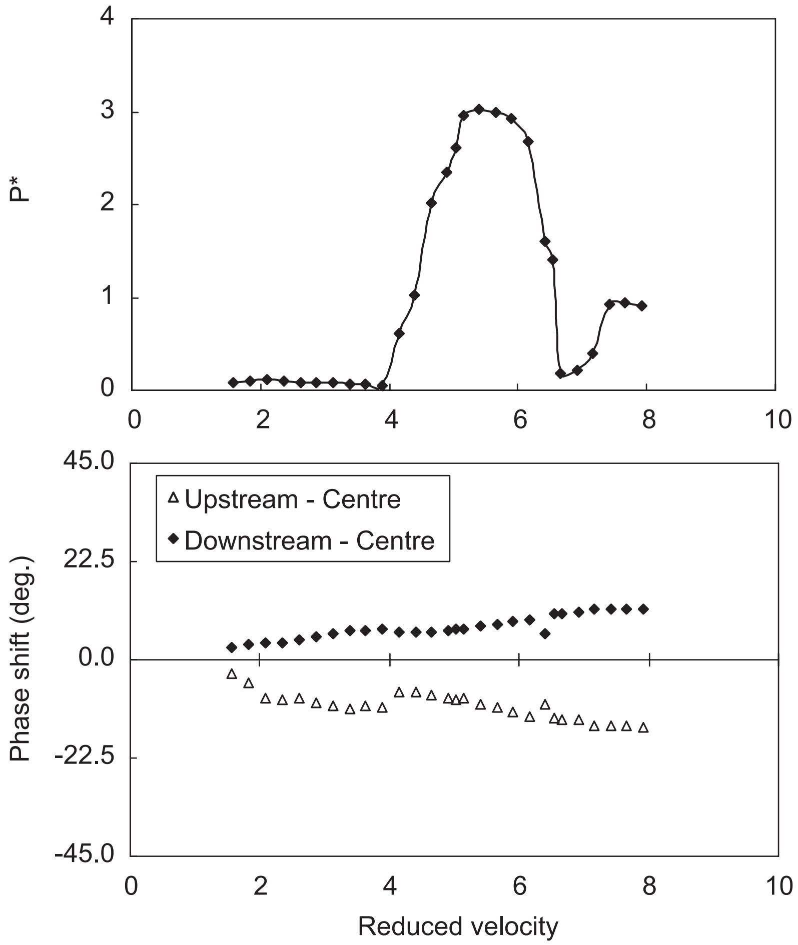


Fig. 9. Normalised acoustic pressure at the reference microphone and variations in the phase angle of the acoustic pressure measured at two different locations upstream (2.34$D$) and downstream (1.74$D$) of the reference microphone as functions of the reduced velocity. $L/D = 2.5$, $D = 21.8$ mm.

circumference are needed to determine the instantaneous lift force and its phase. In order to assess the possibility of acquiring lift phase data from pressure measurements at selected points on the surface of the cylinder, additional experiments were performed to measure the fluctuating surface pressure on the cylinder surface using the pressure tap configuration shown in Fig. 3. Only one spacing ratio was tested, $L/D = 2.5$, and four different orientations of the pressure tap were considered for both the upstream and the downstream cylinders, $\theta = 45^\circ$, $60^\circ$, $80^\circ$ and $90^\circ$ with respect to the front stagnation point as shown in Fig. 3. A larger diameter cylinder ($D = 19$ mm) was used in these experiments to allow the implementation of the microphone into the cylinder.

The phase difference between the fluctuating surface pressure and the acoustic pressure acting on the top wall of the test section is shown in Fig. 10 for different orientation angles. Although these results resemble the general features of the lift phase angle, including the phase jumps at the start and end of the pre-coincidence resonance range, the phase values and the associated jumps are found to be strongly dependent on the orientation of the pressure tap. Thus, it is clearly difficult to obtain reliable phase data from measurements of the fluctuating pressure at selected points on the surface of the cylinder.

Referring to Figs. 6(b), 7(b) and 8(b) again, the behaviour of the phase difference during the pre-coincidence resonance range is seen to be distinctly different from that during the coincidence resonance range. This difference supports the supposition that these resonance ranges are caused by different excitation mechanisms. As mentioned earlier, the pre-coincidence resonance is excited by the instability of the shear layers in the gap, whereas the coincidence resonance is excited by vortex shedding in the wake of the downstream cylinder. The latter mechanism is similar to that causing acoustic resonance for a single cylinder in a duct.

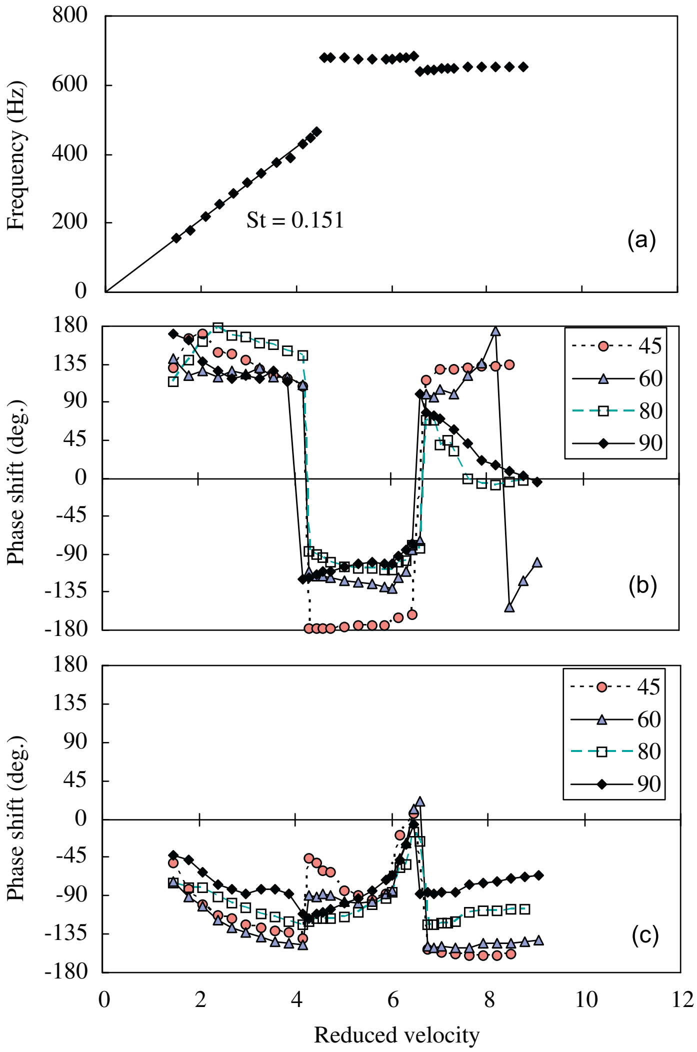


Fig. 10. (a) Frequency of vortex shedding and (b, c) phase angle between the fluctuating pressure on the cylinder surface and the acoustic pressure on the top wall, for (b) upstream cylinder and (c) downstream cylinder. $L/D = 2.5$, $D = 19\,\mathrm{mm}$.

## 6. Force decomposition analysis

Mohany and Ziada (2007) measured the fluctuating lift force acting on a *single* cylinder during self-excited acoustic resonance. They compared the phase shift between the lift force and acoustic pressure with those reported in the literature for the cases of externally applied sound (Hall et al., 2003) and forced oscillating cylinder (Carberry et al., 2001). Mohany and Ziada (2007) also used the force decomposition technique and compared the acoustic resonance results, shown in Fig. 11, with those of forced oscillating cylinder (Sarpkaya, 1978). They concluded that *the phase relationship between the dynamic lift force and the resonant acoustic pressure, which is investigated here, is similar to the phase relationship between the lift force and the cylinder displacement for the case of forced oscillating cylinder.* In the following, a similar approach is used to decompose the lift forces on the tandem cylinders into the in-phase and the out-of-phase components with respect to the acoustic pressure. The objective is to gain more insight into the excitation mechanism and the process of energy transfer from the flow to the acoustic field. As mentioned earlier, the sound produced by vortex shedding, which is the excitation source causing acoustic resonance, is similar to that produced by a dipole sound source located at the cylinders. This dipole source can be expressed in terms of the dynamic lift force generated by vortex shedding on the cylinder (Blevins, 2001). Since the measured dynamic lift force represents the integrated effect of the unsteady flow field, *its phase is equivalent to the phase of the integrated flow excitation with respect*

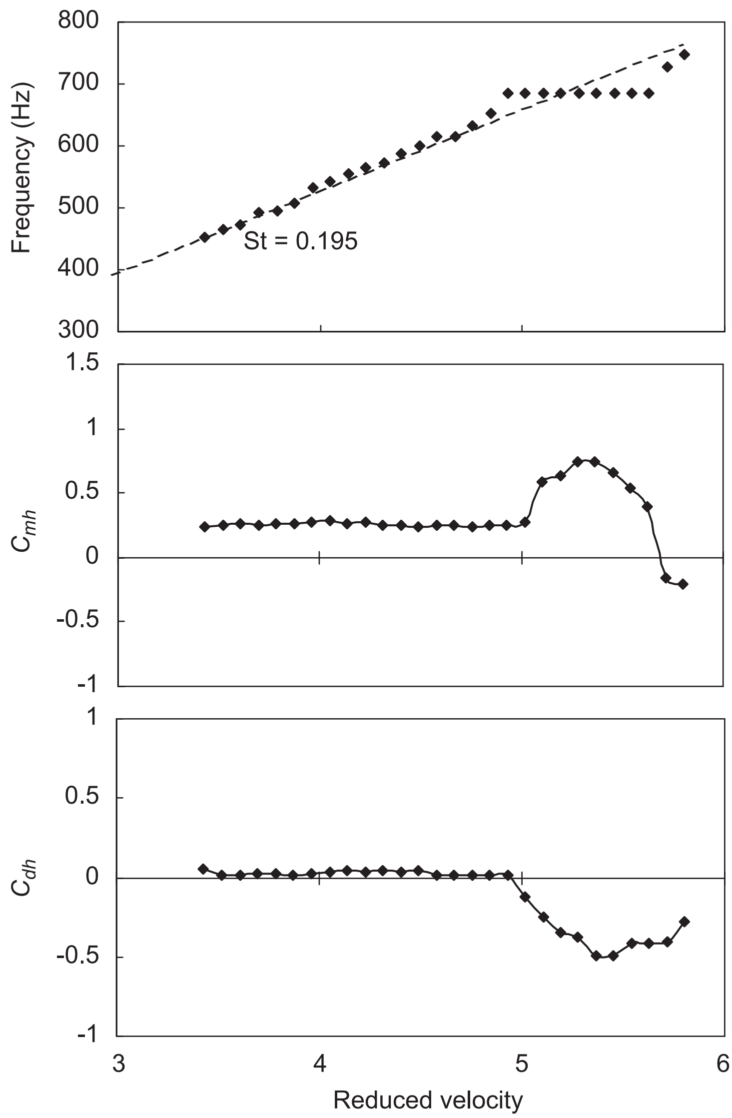


Fig. 11. Behaviour of the in-phase ($C_{mh}$) and out-of-phase ($C_{dh}$) components of the lift force versus reduced velocity for a single cylinder; $D = 15.8$ mm [from Mohany and Ziada (2005b)].

*to the resonant sound pressure field*. Thus, analogous to the case of cylinder vibration (Sarpkaya, 1978), the out-of-phase component of the dynamic lift force, with respect to the resonant sound field, is opposite the acoustic particle velocity of the sound field, and is therefore associated with the dissipation of energy from the sound filed into the flow field. *Only when this component is negative would energy be transferred from the flow to the sound field and acoustic resonances may be excited.*

As can be seen in Fig. 4, the dynamic lift force can be assumed to be sinusoidal, especially within the resonance range, with a dominant frequency equal to the vortex-shedding frequency. This can be expressed as follows:

$$F_{\mathrm{Lift}}(t) \approx \frac{1}{2}\rho U^2 D\ell C_L \sin(2\pi f_v t + \phi_{\mathrm{Lift}}), \tag{4}$$

where $C_L$ is the root mean square amplitude of the fluctuating lift coefficient and $\phi_{\mathrm{Lift}}$ is the phase shift between the dynamic lift force and the resonant sound pressure. Therefore, the dynamic lift coefficient can be expressed as

$$C_L(t) = C_L \sin(2\pi f_v t + \phi_{\mathrm{Lift}}), \tag{5}$$

By means of the force decomposition analysis proposed by Sarpkaya (1978), the in-phase and the out-of-phase components of the lift force, or the inertia and the drag coefficients of the lift force, respectively, can be obtained as

$$C_L(t) = [C_L \cos(\phi_{\mathrm{Lift}})]\sin(2\pi f_v t) + [C_L \sin(\phi_{\mathrm{Lift}})]\cos(2\pi f_v t),$$
$$C_L(t) = C_{mh}\sin\omega t - C_{dh}\cos\omega t, \quad (6)$$

In this equation, $\omega$ is the circular frequency of the vortex shedding, $C_{mh}$ and $C_{dh}$ are the in-phase and out-of-phase components of the lift force with the resonant sound pressure, respectively. These components for $L/D = 2.5$ are shown in Fig. 12 for both the upstream and downstream cylinders. As already mentioned, the lift force components on the downstream cylinder are dominant. Moreover, the out-of-phase component, $C_{dh}$, for the downstream cylinder develops into a large negative value "i.e. negative damping" over the velocity ranges corresponding to the pre-coincidence and the coincidence resonances. It is gratifying that this component reduces to almost zero near $U_r = 6.5$, where the acoustic mode is not excited despite the near-coincidence between the vortex-shedding frequency and the resonance frequency, see Fig. 5. This means that during the pre-coincidence and the coincidence resonance, the out-of-phase component of the lift force, $C_{dh}$, is in phase with the acoustic particle velocity of the acoustic mode; see Mohany and Ziada (2007) for more details. Since it is not the sound pressure that affects the vortex shedding but rather the acoustic particle velocity

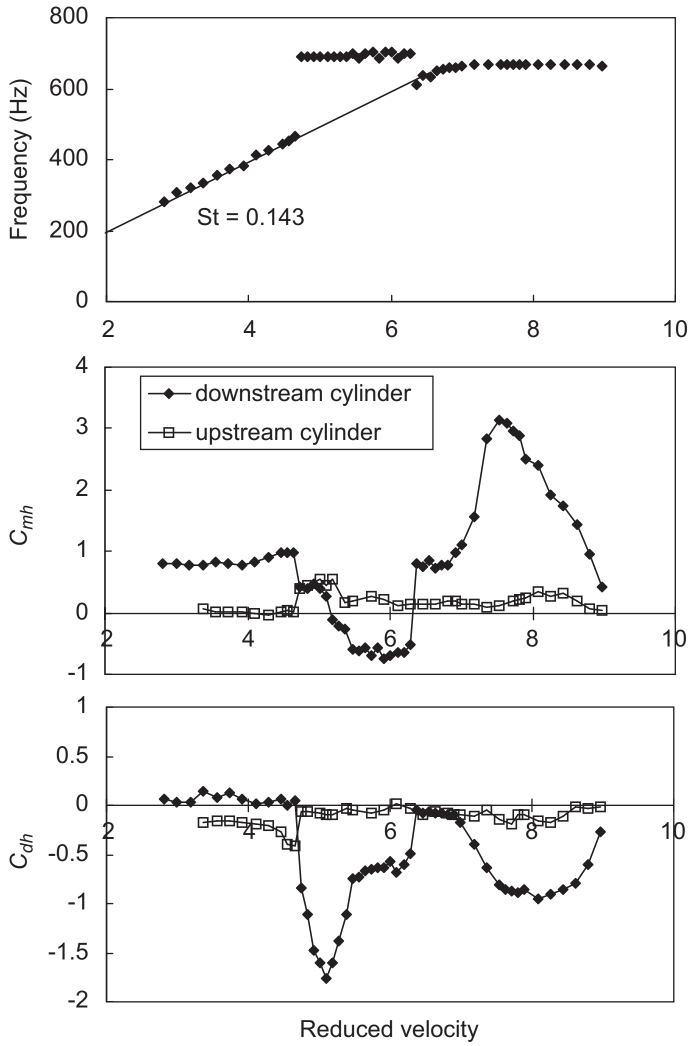


Fig. 12. Frequency of vortex shedding showing the lock-in ranges (top), and decomposition of the lift force into the in-phase ($C_{mh}$) and out-of-phase ($C_{dh}$) components as functions of reduced velocity. $L/D = 2.5$, $D = 15.2$ mm.

(Blevins, 1985), this phasing of events promotes the excitation of the acoustic resonance. Thus, the vortex-shedding process within the resonance ranges acts as an acoustic source which causes a positive energy transfer from the mean flow into the acoustic field.

Regarding the in-phase component, $C_{mh}$, it remains virtually constant, around unity, for the downstream cylinder, except within the resonance ranges. Within the pre-coincidence resonance range, $C_{mh}$ decreases continually with reduced velocity until it becomes negative. Thereafter, it increases rapidly upon the onset of the coincidence resonance and reaches a value of about 3.25 before it starts declining again as the coincidence resonance progresses. Comparing the values of $C_{mh}$ for the two resonance ranges, and recalling that it represents the ''inertia component'', the resonance frequency may be expected to be higher during the pre-coincidence range, due to the negative inertia, than during the coincidence resonance, because of the positive inertia. This expectation was confirmed by the test results, which showed resonance frequencies near 688 Hz for the pre-coincidence resonance and 660 Hz for the coincidence resonance. These observations agree with the results reported by Graf and Ziada (1992) for acoustic resonance of deep cavities. They showed that the effect of the added mass component of the aeroacoustic source is confined to small changes in the acoustic resonance frequency.

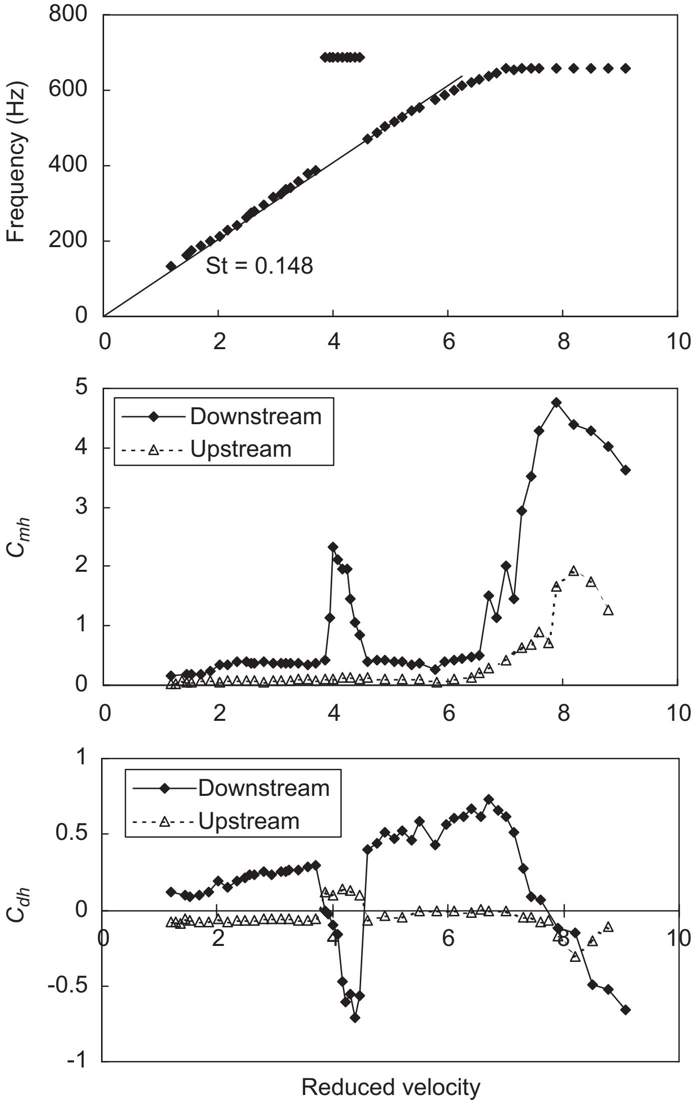


Fig. 13. Frequency of vortex shedding showing the lock-in ranges (top), and decomposition of the lift force into the in-phase ($C_{mh}$) and out-of-phase ($C_{dh}$) components as functions of reduced velocity. $L/D = 1.75$, $D = 18.4$ mm.

All the features described above for the case with $L/D = 2.5$ are seen to be exemplified in the results of the cases with $L/D = 1.75$ and 3, which are shown in Fig. 13 and 14, respectively. Most notable is the dominance of the lift force on the downstream cylinder; the relatively large negative values of $C_{dh}$ on the downstream cylinder during the resonance ranges and its vanishing value between the two resonance ranges; and the larger value of $C_{mh}$ on the downstream cylinder during the coincidence resonance than that during the pre-coincidence resonance, which produces a lower resonance frequency during coincidence than during pre-coincidence resonance. For the case of $L/D = 1.75$, $C_{dh}$ assumes a larger positive value between the two resonance ranges. This is because the two resonance regimes are separated by a much wider reduced velocity range in this case than in the other two cases with larger spacing ratios.

Further scrutiny of Figs. 12–14 reveals the general trend of the lift force components as the spacing ratio is decreased. Considering the $C_{dh}$ component first, its value during pre-coincidence resonance becomes smaller and that during coincidence resonance gains strength as the spacing ratio is decreased. The in-phase, or added mass, component, $C_{mh}$, also shows a well-defined trend. Its coincidence resonance component increases as the spacing ratio is decreased, whereas its pre-coincidence resonance component starts with a large negative value at $L/D = 3$, becomes smaller, but still negative, at $L/D = 2.5$, and then changes to a positive value at $L/D = 1.75$.

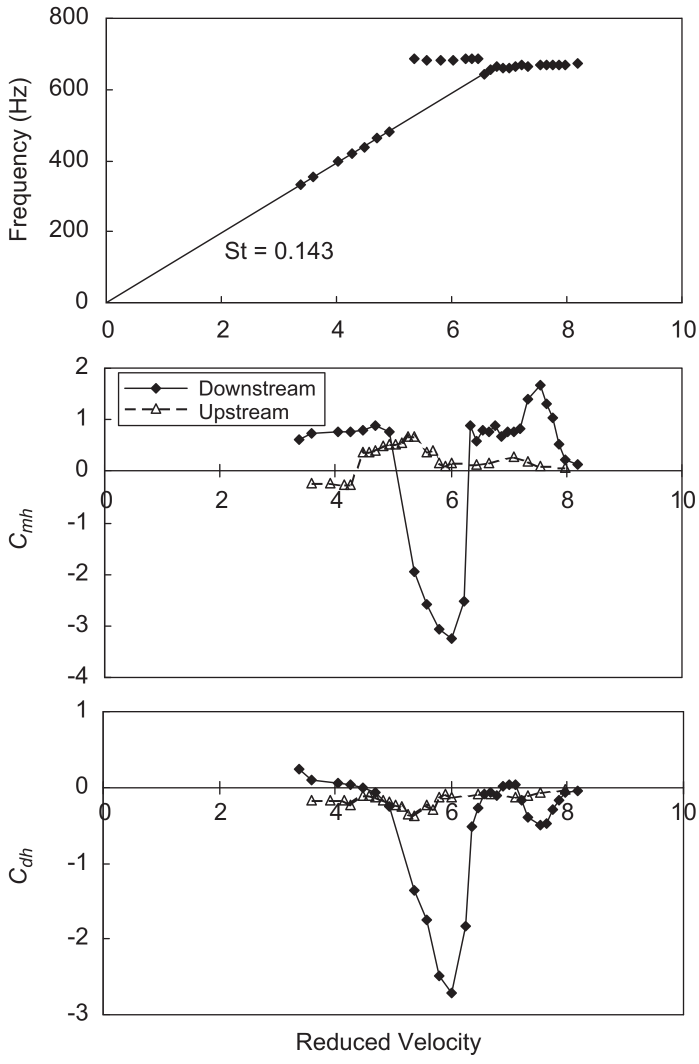


Fig. 14. Frequency of vortex shedding showing the lock-in ranges (top), and decomposition of the lift force into the in-phase ($C_{mh}$) and out-of-phase ($C_{dh}$) components as functions of reduced velocity. $L/D = 3$, $D = 12.7$ mm.

## 7. Conclusions

The effect of sound on the dynamic lift force for two tandem cylinders in cross-flow was investigated for three spacing ratios within the proximity interference region. The dynamic lift force was measured directly during self-excited acoustic resonance, and the lift force coefficients at off-resonance conditions were compared with those available in the literature. Measurements of pressure fluctuations on the cylinder surface were also performed to compare their phase characteristics with those belonging to lift force which was directly measured by means of the force transducer. The following conclusions are drawn.

1. The lift coefficients measured in the absence of acoustic resonance agree reasonably well with those reported in the literature.
2. There is an abrupt increase in the dynamic lift coefficient during acoustic resonance. For the tested cases, this increase ranges from 4 to 6 folds of its value before the onset of resonance.
3. The onset and subsidence of the pre-coincidence resonance is associated with abrupt changes in the phase difference between the lift force and the sound pressure, especially for the downstream cylinder. The coincidence resonance however is not associated with abrupt changes in the lift force. This confirms the supposition that these resonance ranges are generated by different excitation mechanisms.
4. The phase of pressure fluctuations on the cylinder surface is orientation dependent and does not lead to conclusive results regarding the excitation mechanism.
5. The lift force components on the downstream cylinder are dominant. The out-of-phase component, $C_{dh}$, controls the occurrence of acoustic resonance. It becomes negative during the pre-coincidence and the coincidence acoustic resonance ranges, indicating that this lift component becomes in-phase with the acoustic particle velocity at the cylinders.
6. The in-phase component of the lift force on the downstream cylinder, $C_{mh}$, affects the frequency of the acoustic resonance. Since it is substantially higher during the coincidence resonance range, the resonance frequency of this range is lower than that for the pre-coincidence resonance range.

## References

Alam, Mahbub Md., 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 91, 139–154.
Anagnostopoulos, P., 2002. Flow Induced Vibrations in Engineering Practice. WIT Press.
Blevins, R.D., 1985. The effect of sound on vortex shedding from cylinders. Journal of Fluid Mechanics 161, 217–237.
Blevins, R.D., 2001. Flow-Induced Vibration, second ed. Krieger Pub Co, USA.
Blevins, R.D., Bressler, M.M., 1993. Experiments on acoustic resonance in heat exchanger tube bundles. Journal of Sound and Vibration 164, 503–533.
Bishop, R.E.D., Hassan, A.Y., 1964. The Lift and Drag Forces on a Circular Cylinder Oscillating in a Flowing Fluid. In: Proceedings of the Royal Society, London. Series A, 277, pp. 51–75.
Carberry, J., Sheridan, J., Rockwell, D., 2001. Forces and wake modes of an oscillating cylinder. Journal of Fluids and Structures 15, 523–532.
Fitzpatrick, J.A., 1986. A design guide proposal for avoidance of acoustic resonances in in-line heat exchangers. ASME Journal of Vibrations, Acoustics, Stress and Reliability in Design 108, 296–300.
Govardhan, R., Williamson, C.H.K., 2000. Modes of vortex formation and frequency response of a freely vibrating cylinder. Journal of Fluid Mechanics 420, 85–130.
Graf, H.R., Ziada, S., 1992. Flow induced acoustic resonance in closed side branches: an experimental determination of the excitation source. In: Proceedings of the 3rd International Symposium on Flow-Induced Vibration and Noise, vol. 7. ASME WAM, Anaheim, pp. 63–80.
Hall, J.W., Ziada, S., Weaver, D.S., 2003. The effect of applied sound on vortex shedding from two tandem cylinders. Journal of Fluids and Structures 18, 741–758.
Igarashi, T., 1981. Characteristics of the flow around two circular cylinders arranged in tandem—1st report. Bulletin of JSME 24 (188), 323–331.
Mohany, A., Ziada, S., 2005. Flow excited acoustic resonance of two tandem cylinders in cross flow. Journal of Fluids and Structures 21, 103–119.
Mohany A., Ziada, S., 2006. A parametric study of the resonance mechanism of two tandem cylinders in cross-flow. American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP, vol. 9. In: Proceedings of the ASME Pressure Vessels and Piping Conference 2006, pp. 63–71 (also Journal of Pressure Vessel Technology, in press).

Mohany, A., Ziada, S., 2007. Effect of flow-sound interaction on the dynamic lift force of a single cylinder in cross-flow. Dynamics of Continuous, Discrete and Impulsive Systems, Series B: Applications and Algorithms 14 (S8), 1–18.
Norberg, C., 2003. Fluctuating lift on a circular cylinder: review and new measurements. Journal of Fluids and Structures 17, 57–96.
Phillips, O.M., 1956. The intensity of aeolian tones. Journal of Fluid Mechanics 1, 607–624.
Sarpkaya, T., 1978. Fluid forces on oscillating cylinders. ASCE Journal of the Waterway-Port, Coastal and Ocean Division 104, 275–290.
Sarpkaya, T., 2004. A critical review of the intrinsic nature of vortex-induced vibrations. Journal of Fluids and Structures 19, 389–447.