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VORTEX SHEDDING AND ACOUSTIC RESONANCE OF SINGLE AND TANDEM FINNED CYLINDERS

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ABSTRACT

The effect of fins on vortex shedding and acoustic resonance is investigated for isolated and two tandem cylinders exposed to cross-flow in a rectangular duct. Three spacing ratios between the tandem cylinders (S/D_e = 1.5, 2 and 3) are tested for a Reynolds number range from 1.6×10^4 to 1.1×10^5. Measurements of sound pressure and flow velocity are performed for bare and finned cylinders with three different fin densities. The effect of fins on the sound pressure generated before the onset of acoustic resonance as well as during the pre-coincidence and coincidence resonance is found to be rather complex and depends on the spacing ratio between cylinders, the fin density and the nature of the flow-sound interaction mechanism.

For isolated cylinders, the fins reduce the strength of vortex shedding only slightly, but strongly attenuate the radiated sound before and during the acoustic resonance. This suggests that the impact of the fins on correlation length is stronger than on velocity fluctuations. In contrast to isolated cylinders, the fins in the tandem cylinder case enhance the vortex shedding process at off-resonant conditions, except for the large spacing case which exhibits a reversed effect at high Reynolds numbers. Regarding the acoustic resonance of the tandem cylinders, the fins promote the onset of the coincidence resonance, but increasing the fin density drastically weakens the intensity of this resonance. The fins are also found to suppress the pre-coincidence resonance for the tandem cylinders with small spacing ratios (S/D_e = 1.5 and 2), but for the largest spacing case (S/D_e = 3), they are found to have minor effects on the sound pressure and the lock-in range.
Keywords: Finned Cylinders, Vortex Shedding, Acoustic Resonance, Tandem Cylinders

1. INTRODUCTION

Vorticity shedding from cylinders in cross-flow can cause structural vibration of the cylinders or acoustic resonance of the surrounding fluid volume. Heat exchanger tube bundles are particularly liable to this type of excitation as well as to other flow excitation mechanisms such as fluid-elastic instability and turbulent buffeting. Comprehensive reviews of the flow-excitation mechanisms in tube arrays have been published by Paidoussis [1], Weaver and Fitzpatrick [2], Weaver [3] and Ziada [4]. The mechanisms of vortex shedding and acoustic resonance have also been investigated extensively for the simpler cases of isolated cylinders and two cylinders in various arrangements, e.g. tandem, side-by-side and staggered arrangements. Beside the relevance of these simple configurations to many engineering applications, clarifying the effect of proximity on the flow across two cylinders, in

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comparison with that of the isolated cylinder, is helpful in understanding the effect of cylinder arrangement and spacing in the more complex cases of tube arrays.

The flow regimes for two tandem cylinders with different spacing ratios were studied by many researchers [e.g. 5 - 11]. Ljungkrona et al. [7] showed that the flow behavior changes significantly at high turbulence intensity. Lin et al. [8] have used high-density particle image velocimetry to study the gap and near wake flow of two cylinders in tandem at Re = 10000. They were able to show clearly the small scale Kelvin-Helmholtz vortices in the unstable shear layers in the gap between the cylinders. Alam et al. [9] demonstrated the strong dependence of the drag and lift force on the spacing between the cylinders.

In its simplest form, flow-excited acoustic resonance occurs when the frequency of vortex shedding, f_v, approaches the acoustic resonance frequency of the duct housing the cylinders, f_a. The excited acoustic modes are usually those consisting of standing waves in a direction normal to the flow and the cylinder axis. A key feature of this mechanism is the occurrence of a “lock-in” velocity range over which the resonant acoustic field entrains the vortex shedding phenomenon and thereby the shedding frequency remains constant until the resonance subsides and the vortex shedding process regains its natural frequency according to the Strouhal number relationship. For the case of two tandem cylinders, this rather classical excitation mechanism was also observed to start near the coincidence between the acoustic and the shedding frequencies. Mohany and Ziada [12, 13] have classified this resonance range, for the two tandem cylinder case, as the “coincidence resonance” in order to differentiate it from the “pre-coincidence range” which occurs at lower flow velocities as discussed in the following.

The effect of sound on vortex shedding from single cylinders was investigated by Blevins [14]. He observed that the sound eliminates the random wander of the vortex shedding frequency and correlate the vortex shedding along the cylinder span. He concluded that the entrainment of the vortex shedding is produced by the acoustic velocity rather than the sound pressure induced by the sound wave. Hall et al. [15] studied the effect of sound on vortex shedding from tandem cylinders. They reported that the lock-in envelope for tandem cylinders is larger than that for single cylinders. They also observed that the sound is able in some cases to promote the vortex-shedding in the gap between the cylinders. Blevins and Bressler [16] and Mohany and Ziada [12] tested isolated bare cylinders to characterize the effect of the duct geometry, Mach number and Reynolds number on the resonant sound levels. Mohany and Ziada [12, 13] investigated the effect of the gap between two tandem cylinders on the excitation mechanism of acoustic resonance. They discovered a new lock-in velocity range which occurs at a lower reduced velocity. They classified this range as the pre-coincidence resonance because it occurs and subsides before the flow velocity reaches the coincidence condition. They concluded also that acoustic resonances of in-line tube bundles must be excited by the pre-coincidence resonance mechanism which is observed for tandem cylinders. More recently, Hanson and Ziada [16] investigated the effect of acoustic resonance on the dynamic fluid forces acting on the tubes of in-line and staggered tube bundles and suggested a design approach to estimate these forces. All these studies focused on bare or smooth cylinders, whether they were isolated, in tandem, or in array configurations.

Finned tubes are used extensively in heat exchangers. Acoustic resonance has been reported also for finned tube bundles and the overall sound pressure levels can be higher than that for bare tubes as illustrated by Nemoto et al. [18]. In order to understand the effect of fins on vortex shedding, few studies were performed on isolated finned cylinders. Brevoort and Rollin [19] studied the characteristics of air flow across finned cylinders by measuring the average velocity using pitot tubes for smooth and finned tubes of different fin densities and fin widths. Carvajal-Mariscal et al. [20] studied the flow dynamics between inclined fins on a tube and found an increase in the drag coefficient by 50 % over that in the case of bare tube. Hamakawa et al. [21] investigated the effect of fin density and shape on the vortex shedding from a single finned cylinder for Reynolds number between 1.1×10^4 and 1.1×10^5. They observed an increase in the vortex shedding correlation length when the fins were added. Ziada et al. [22] studied the effect of serrated fins on vortex shedding from single cylinders in the subcritical range. They also found the correlation length to become longer and the velocity fluctuations at the vortex shedding frequency to become stronger with the increase in the fin density. While these studies suggest that the addition of fins enhances the vortex shedding process from isolated cylinders, the effect of this enhancement on the acoustic resonance mechanism has not been clarified. In addition, the effect of fins on the coincidence and pre-coincidence acoustic resonance mechanisms has not been explored either.

The present work investigates the effect of fins on the acoustic resonance mechanism for isolated and two tandem cylinders. Three different fin densities and three different spacing ratios between the cylinders are considered. Measurements of the mean and fluctuating velocity profiles in the wake and the sound pressure level at acoustic resonance are compared with their counterparts obtained from equivalent bare cylinders. The fins were manufactured individually and assembled along the cylinders to minimize deviations in the fin geometry along the cylinder length and the azimuthal angle. Such deviations proved to be problematic in previous studies as reported by Ziada et al. [22].

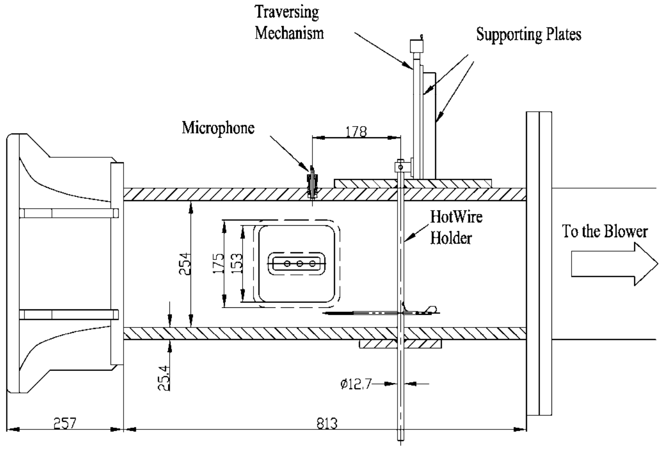

Figure 1. Details of the test section (All dimensions in mm.)

2. EXPERIMENTAL SET-UP

The experiments were conducted in an open circuit, low speed wind tunnel with an acrylic test section of 254 mm in height and 76.2 mm in width. The dimensions of the test section were carefully chosen so that the vortex shedding frequency is coincident with the acoustic natural frequency of the test section well below the maximum attainable velocity of the wind tunnel. This set-up therefore facilitated the study of the effect of fins on vortex shedding at resonant and non-resonant conditions. The maximum turbulence intensity in the test section was measured to be 1.5 %. Figure (1) shows the details of the test section.

A parabolic contraction was used at the test section inlet to achieve a uniform velocity profile with as small as possible boundary layer thickness. A diffuser was used between the test section outlet and the blower inlet to reduce the pressure loss and thereby increase the maximum attainable flow velocity during the tests.

Since the volume of the cylinders is small compared to the volume of the test section, their effect on the speed of sound can be neglected and the frequency of the transverse acoustic mode of the test section can be calculated from the relation:

$$f_a = ic/2B\,, \quad i = 1, 2, 3, \ldots \tag{1}$$

where c is the speed of sound in air and B is the height of the test section.

The acoustic natural frequency of the first mode for the test section (i =1) is calculated to be f_a = 681 Hz. The measurements show that the acoustic natural frequency of the test section is about 686 Hz, which is within 1% of the estimated value.

A hotwire anemometry system was used to measure the mean and the fluctuating flow velocity. A manual mechanism was utilized to traverse the hotwire probe vertically across the wake

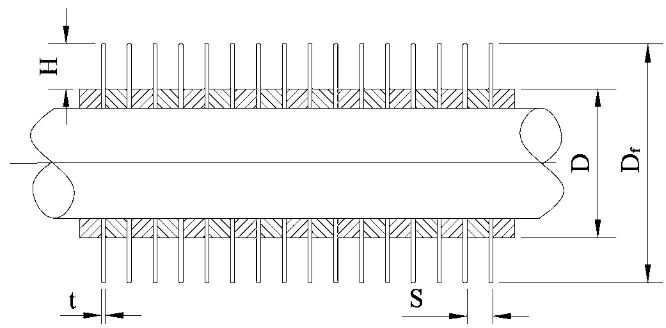

Figure 2. Details of the finned cylinders

of the cylinders with a precision of 0.01 mm. A pressure microphone was used to measure the sound pressure at the top wall of the test section. The frequency response of the microphone is flat over the range from 10 Hz to 25 kHz within ±1 dB. It was installed flush with the internal top surface of the test section so that it does not disturb the flow. All the microphone measurements were taken above the downstream cylinder. The hotwire anemometry system including the traversing mechanism was removed from the test section during the sound pressure measurements. A 16 bit 4-channel card, equipped with an anti-aliasing filter, was used for data acquisition.

Cylinders with three different fin densities were selected for this study. One of the cylinders was designed as a small-scale model of a finned tube widely used in industrial applications. The dimensions of the other two finned cylinders were similar except that the fin density was different to investigate its effect on the vortex shedding process. As shown in Fig. 2, the finned cylinders were made of precision polished bare cylinders on which discs and spacers were fitted tightly to model the fins. The required fin density was obtained by changing the width of the spacers.

The diameter of the bare tubes used in this study is the same as the effective diameter of the finned cylinder as defined by Mair et al. [23]:

$$D_e = \frac{(S-t)D + tD_f}{S} \tag{2}$$

where D_e is the effective diameter, S is the fin pitch, t is the fin thickness and D_f is the fin outer diameter.

As reported by Mair et al. [23] and Ziada et al. [22], isolated finned cylinders are found to have the same vortex shedding frequency as bare cylinders of the same effective diameter. The tests were therefore planned such that the coincidence of the vortex shedding frequency, from either the bare or the finned cylinders, occurs at the same flow velocity and thus at the same Mach number and dynamic head, which are known to be important parameters affecting sound generation by vortex

Table 1. DIMENSIONS OF TESTED CYLINDERS

	Finned Cylinders			Bare Cylinders	
	Type I	Type II	Type III	Type I	Type II
Length (mm.)	76	76	76	76	76
Root Diameter (mm.)	15	15	15	16	17.5
Fin Thickness (mm.)	0.381	0.381	0.381	—	—
Fin Height (mm.)	4.5	4.5	4.5	—	—
Fin Spacing (mm.)	4.4	2.2	1.0	—	—
Fin density (fins/inch)	5.3	9.8	18.2	—	—
Effective Diameter (mm.)	15.7	16.3	17.5	16	17.5

shedding (see e.g. Blevins and Bressler [16], and Mohany and Ziada [12]). Figure 2 shows the details of the finned cylinders, and Table 1 lists the dimensions of all tested cylinders. The distance between the cylinders for the cases of tandem cylinders were chosen to represent three different flow regimes. These spacing ratios are S/De = 1.5, 2, and 3, where S is the center to center distance between the cylinders.

The test results are presented here in terms of dimensionless parameters such as the frequency ratio, the reduced velocity, the Strouhal number and the normalized acoustic pressure. The first parameter presents the ratio between the vortex shedding frequency f_v and the acoustic resonance frequency of the test section f_a. The reduced velocity V_r is defined as:

$$V_r = V/D_e f_a \tag{3}$$

where V is the free stream velocity, D_e is the effective cylinder diameter and f_a is the acoustic resonance frequency of the test section.

The Strouhal number of vortex shedding is given by:

$$St = f_v D_e / V \tag{4}$$

Finally, the normalized sound pressure at the frequency of vortex shedding P_v^* is defined by:

$$P_v^* = \frac{P_v}{\frac{1}{2}\rho V^2 M} \tag{5}$$

where P_v is the root mean squared amplitude of sound pressure at the vortex shedding frequency, ρ is the density of the air,

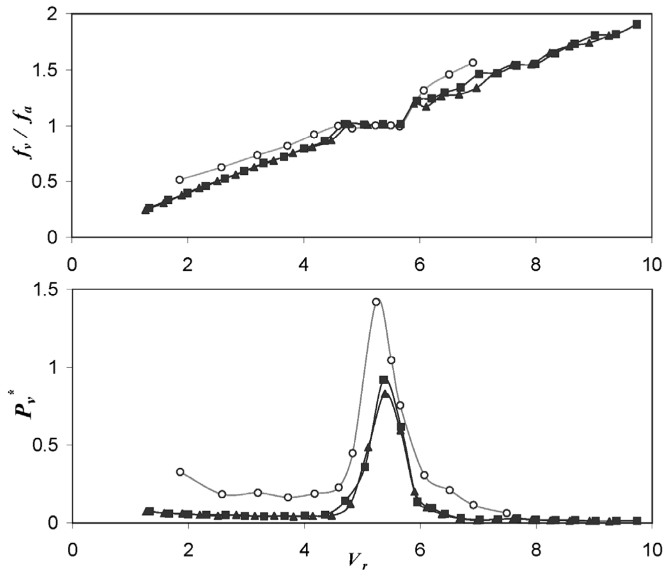

Figure 3. Frequency ratio (f_v/f_a) and the normalized sound pressure (P_v^*) as functions of the reduced velocity (V_r) for bare *single* cylinders. ■ , bare cylinder I; ▲, bare cylinder II; ○, Blevins and Bressler [16].

and M is the Mach number. This normalized form of the far field sound generated by vortex shedding from a cylinder in cross-flow has been shown by Blevins [24] to be a function of the dynamic lift coefficient acting on the cylinder and the process of vortex shedding and its associated dynamic lift coefficient and correlation length.

3. RESULTS OF SINGLE CYLINDERS

3.1. Effect of Fins on the Aeroacoustic Response of Single Cylinders

First, the aeroacoustic response of the single bare cylinders was studied and compared with the results available in the literature. The results of this study are shown in Fig. 3, which gives the vortex shedding frequency and the normalized acoustic pressure as functions of the reduced velocity. It is seen that the vortex shedding frequency increases linearly with the reduced velocity and the sound pressure increases sharply during the lock-in range which occurs near the frequency coincidence ($f_v/f_a \approx 1$). The results of bare cylinders I and II are almost identical and are in agreement with those reported by Blevins and Bresseler [16], except that the maximum normalized pressure during the lock-in range is lower in the present experiments. This maximum value has been addressed by Blevins and Bressler [16] who suggested the following expression to correlate the maximum sound pressure for different cylinder diameters with an average error of 26%:

$$P_{v\text{-}max} = (12.5\rho V^2/2)(V/c)(D/B) \tag{6}$$

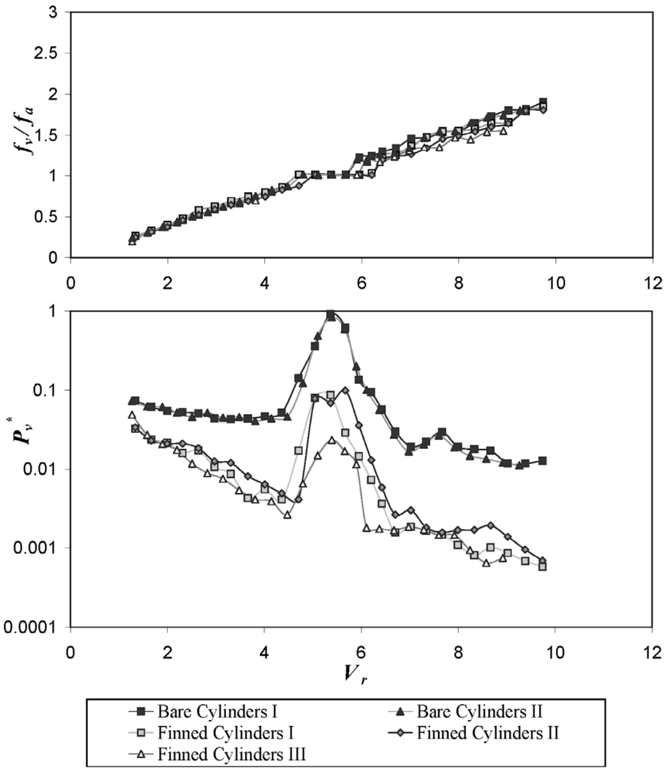

Figure 4. Acoustic response of the bare and finned single cylinders showing the frequency ratio (f_v/f_a) and the normalized sound pressure (P_v^*) as functions of the reduced velocity (V_r)

Using this correlation for the present tests on bare single cylinders I and II, the calculated maximum sound pressures are found to be within 11% of the measured values.

Figure (4) shows the change in the dimensionless vortex shedding frequency f_v/f_a and the dimensionless sound pressure at the vortex shedding frequency P_v^* as functions of reduced velocity V_r for the bare and finned single cylinders. The sound pressure P_v^* before resonance is much higher for the bare cylinders than for the finned cylinders. This is due to the fins that reduce the strength and correlation length of the vortex shedding process by disrupting the flow over the cylinder. This results in higher broadband turbulence and noise levels in the case of finned cylinders. The difference between the values of sound pressure P_v^* for the finned and the bare cylinders increases with the increase in flow velocity, which indicates that the effect of the fins on disrupting the flow becomes more significant at higher Reynolds numbers.

As in the case of bare cylinders, the finned cylinders have excited the first acoustic mode and a lock-in range between the vortex shedding frequency and the acoustic resonance frequency has been observed as shown in Fig. 4. However, the fins reduce the resonance intensity by more than an order of magnitude. There is no significant difference in the sound pressure level between finned cylinders I and II. However, for the finned cylinder III, which has the highest fin density, there is a significant difference as the sound pressure at resonance is substantially lower than that for the other cases of finned cylinders. Post the resonance range, $V_r > 7$, P_v^* for the bare cylinders continues to be higher than that for the finned cylinders. The difference in the value of P_v^* does not change much with farther increases in the reduced velocity.

3.2. Effect of Fins on the Wake of Single Cylinders

In order to gain more insight into the effect of fins on the flow behavior, hotwire measurements were performed at a reduced velocity corresponding to before the onset of resonance. For this purpose, finned cylinder II, with the intermediate fin density, was used and the results are compared with those of bare cylinder I, whose diameter is similar to the equivalent diameter of finned cylinder II. All velocity measurements were carried out at a distance of x/D_e=2.5 downstream of the cylinder. Hotwire measurements at velocities within the lock-in range were not possible because of the high level of noise and vibration during the acoustic resonance.

The results of the hotwire measurements at $V_r = 3.2$ (Re = 3.7×10^4**)** are shown in Fig. 5. The mean velocity V, normalized by the free stream velocity V_o is plotted in Fig. 5a against the transverse distance y, measured from the cylinder centerline and normalized by the effective diameter D_e. A hump is observed in the mean velocity profile near the wake boundaries of the bare cylinder as well as the finned cylinder. However, the mean velocity increases by 11% above the approach velocity in the case of the finned cylinder while it is about only 1% in the case of the bare cylinder. For the finned cylinder, the mean velocity decreases at a higher rate and the velocity deficit is substantially larger than in the case of the bare cylinder.

The drop in the total streamwise turbulence intensity level near the wake centerline plane is observed to be larger in the case of the finned cylinder as shown in Fig. 5(b). However, the maximum level of turbulence intensity is similar in both cases and is about 30%. Figure 5(c) shows the profile of the normalized velocity fluctuation associated with the fundamental vortex shedding component, which is defined by $Tu_v = v/V$, where v is fluctuating velocity at the vortex shedding frequency. The profiles of the bare and finned cylinders appear similar, with the maximum fluctuation amplitude occurring at the same y/D_e location. However, the maximum amplitude of velocity fluctuation is about 20% lower in the case of the finned cylinder, which implies that the vortex shedding process is weaker for the finned cylinder than the bare cylinder. This agrees with the results shown in Fig. 4, which show that the sound pressure is higher for the bare cylinder case at a reduced velocity before the onset of resonance (V_r = 3.2), and also that the acoustic resonance is stronger for the bare cylinders than that generated by the finned cylinders. Thus, the fins appear to disrupt the vortex shedding process and weaken the flow-

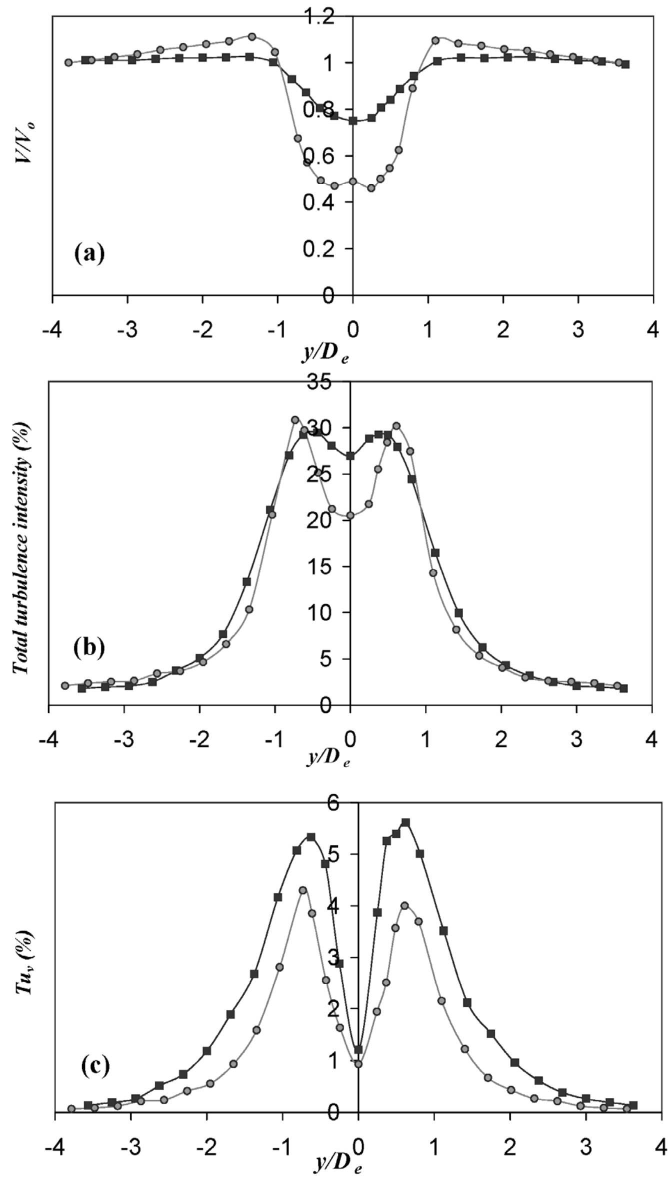

Figure 5. Wake characteristics for single bare cylinder I and finned cylinder II. (a) mean velocity profiles; (b) total turbulence intensity profiles; (c) fluctuation velocity at the vortex shedding frequency. Measurements performed at x/D_e = 2.5 and V_r = 3.2 (*Re* = 3.7 x 10^4); —■—, bare cylinder I; —●—, finned cylinder II.

excited acoustic resonance mechanism in the case of isolated cylinders.

4. RESULTS OF TANDEM CYLINDERS

The behavior of the flow over the tandem cylinders is quite different from that observed for flow over single cylinders, especially when the mechanism of flow-excited acoustic resonance is considered. The presence of the fins creates additional complexities in the tandem cylinder case because of the normal vortex-edge interaction (Rockwell [25]) which occurs when a vortex impinges normally on a thin body such as the fins. This situation is experienced by the vortices shed from the upstream cylinder, which are initially also affected by the fins on the upstream cylinder.

Although the fins are shown to weaken vortex shedding and acoustic resonance for single cylinders, these same fins seem to be capable of producing the opposite effect for tandem cylinders as will be shown in the following section. Before discussing the effect of fins on the tandem cylinders with different spacing ratios, it is helpful to remember that tandem cylinders can generate acoustic resonance over two separate velocity ranges. As mentioned in the introduction section, these are classified by Mohany and Ziada [12] as the pre-coincidence and the coincidence resonance ranges. The effect of fins on the vortex shedding process and the acoustic resonance of these ranges is discussed in the following.

4.1. Tandem Cylinders with S/D_e = 1.5

4.1.1. Effect of fins on the aeroacoustic response of tandem cylinders with S/D_e = 1.5. Figure 6 shows the dependence of the dimensionless frequency and the normalized sound pressure at the vortex shedding frequency on the reduced velocity for the bare and tandem cylinders with a spacing ratio of S/D_e = 1.5. Before the onset of resonance, the frequency of vortex shedding increases linearly with the velocity and the Strouhal number, based on the effective diameter, seems to be the same in all cases. The sound pressure P_v^* for all cases of finned cylinders is clearly higher than that for the bare cylinders, which is contrary to the case of single cylinders, as can be seen from comparing Figs. 4 and 6.

Regarding the excitation of acoustic resonance, it is clear that the fins promote the onset of resonance; first, the resonance starts at lower reduced velocities for all finned cylinder cases than for the bare cylinders, and secondly, the resonance starts earlier when the fin density increases. Increasing the diameter also has the effect of promoting the onset of resonance, which is the case for bare cylinder II. However, the fins have a more significant effect, which cannot be attributed to the increase in effective diameter. For example, the resonance starts in the case of finned cylinders I before the bare cylinders II, although the effective diameter of the finned cylinders (15.7 mm) is smaller than the diameter of the bare cylinders (17.5 mm). Thus, the early onset of resonance for the finned cylinders must be caused by the higher sound pressure observed before the onset of resonance, which facilitates the entrainment of vortex shedding at a lower reduced velocity. This confirms the supposition that the effect of the fins is not solely due to an increase in the effective diameter.

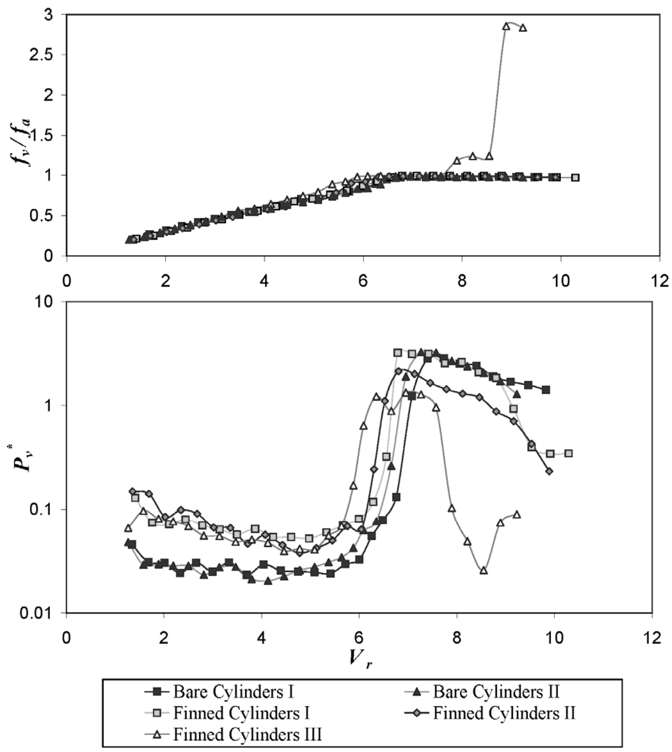

Figure 6. Frequency ratio (f_v/f_a) and the normalized sound pressure (P_v^*) as functions of the reduced velocity (V_r) for bare and finned tandem cylinders with S/D_e=1.5

At resonance, it is observed that the lock-in is stronger for the bare cylinders. The lock-in gets weaker as the fin density increases. At the beginning of the lock-in, the sound pressure is the same for the bare cylinders and finned cylinders I. However, the sound pressure starts to drop earlier in the case of finned cylinders I, near V_r = 9, which indicates that its lock-in range is narrower. Generally, increasing the fin density is observed to weaken significantly the lock-in of vortex shedding with the acoustic natural frequency of the test section, which is reflected in reducing the sound pressure at resonance and narrowing the velocity range of lock-in.

The third acoustic mode near $f_v/f_a \approx 3$ is seen to be excited for finned cylinders III at a reduced velocity $V_r \approx 9$. This behavior seems to be the result of a pre-coincidence resonance mechanism (Mohany and Ziada, [12]). However, all other tandem cylinders, bare and finned, were not able to excite the third mode within the tested range. This is likely due to the higher turbulence intensity generated by the high density fins which promote the excitation of the third mode. In addition, the acoustic resonance of the first acoustic mode is substantially stronger for all other cases, which results in a wider lock-in range and delays the excitation of the third acoustic mode.

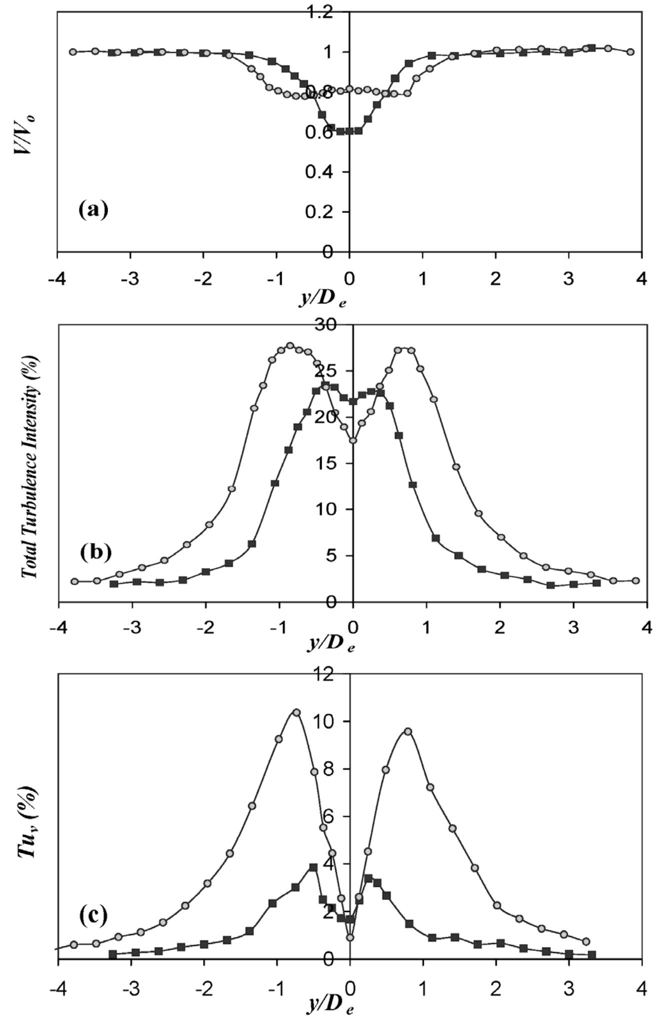

Figure 7. Wake characteristics for *tandem* bare cylinders I and finned cylinder II with S/D_e=1.5; (a) mean velocity profiles; (b) total turbulence intensity profiles; (c) fluctuation velocity at the vortex shedding frequency. Measurements performed at x/D_e = 2.5 and V_r = 3.2 (Re = 3.7 x 10^4); —■—, bare cylinder I; —●—, finned cylinder II.

4.1.2. Effect of fins on the wake of tandem cylinders with *S/De* = 1.5.

Figure 7 shows the results of hotwire measurements performed on the tandem bare cylinders I and the tandem finned cylinders II at a reduced velocity of V_r = 3.2, which is the same as for the velocity measurements shown in Fig. 5 for isolated cylinders. In this case also, the measurements were taken at a downstream distance x/D_e = 2.5 from the downstream cylinder centerline. Figure 7(a) depicts the mean velocity profiles for the bare and finned cylinders. The wake of the finned cylinders is wider than that of the bare cylinders, which is to be expected. However, the deficit in the mean velocity profile for the tandem finned cylinders is substantially smaller, not only than the deficit of the bare cylinders (Fig. 7),

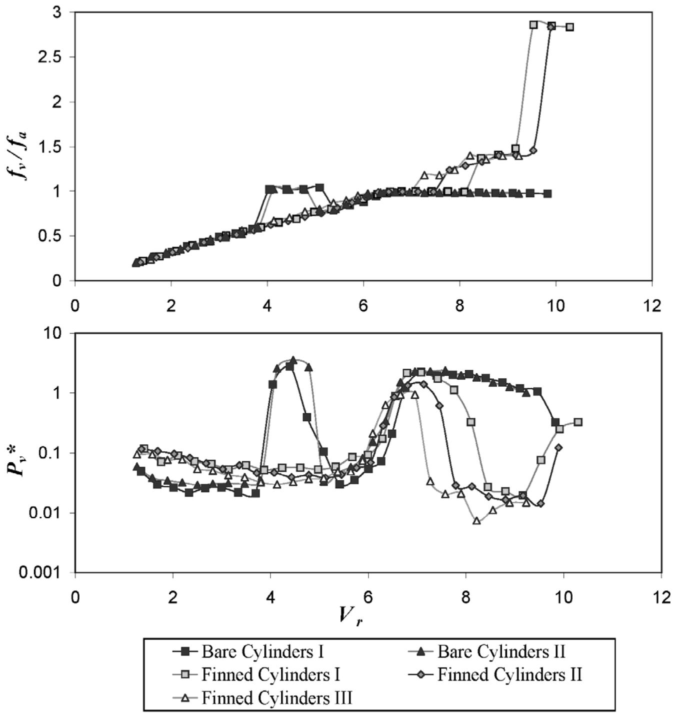

Figure 8. Frequency ratio (f_v/f_a) and the normalized sound pressure (P_v^*) as functions of the reduced velocity (V_r) for bare and finned *tandem* cylinders with S/D_e = 2

but also than that of the single finned cylinder at the same Reynolds number (Fig. 5). This deficit is also found to be smaller than those observed for all other single cylinders, whether finned or not, which have been investigated in this study. The wake is also wider than all of the other cases, which suggests a significant effect of the fins for the case of tandem cylinders.

As can be seen in Fig. 7(b), the total turbulence intensity is higher in case of the finned cylinders and the profile shows a wider wake than the case of the bare cylinders. A reduced turbulence level at the wake center is still observed. Also, the total turbulence intensity profile is substantially wider in this case than in the wake of the single finned cylinder shown in Fig. 5(b), but the maximum turbulence intensity is slightly lower. For the bare tandem cylinders in Fig. 7(b), the turbulence profile does not seem any wider than that for the single bare cylinder which is shown in Fig. 5(b).

The velocity fluctuation at the fundamental vortex shedding component (Tu_v) for the tandem finned cylinders is substantially higher than that for the tandem bare cylinders as shown in Fig. 7(c), which agrees with the sound pressure measurements at this reduced velocity (Fig. 6). This fluctuation velocity (Tu_v) is also higher for the tandem finned cylinders than for the single finned cylinder at the same Reynolds number, Fig. 5(c), which means that the vortex shedding process has been enhanced by adding another finned cylinder at S/D_e=1.5 upstream of the finned cylinder.

4.2. Tandem Cylinders with *S/D*$_e$ = 2

4.2.1. Effect of fins on the aeroacoustic response of tandem cylinders with *S/D*$_e$ = 2. Figure 8 gives the dimensionless frequency and sound pressure of the vortex shedding as functions of the reduced velocity for the bare and finned tandem cylinders. The flow pattern for this case with a spacing ratio of S/D_e = 2 is a quasi-stationary vortex shedding with reattachment. Outside the resonance range, the vortex shedding frequency is seen in Fig. 8(a) to change linearly with the velocity, which suggests the flow pattern remains the same for both the bare and the finned cylinders. It is also seen in Fig. 8(a) that the bare tandem cylinders exhibit both the pre-coincidence and the coincidence resonance ranges of the first acoustic mode.

Before the onset of resonance, Fig. 8(b) shows that the normalized sound pressure at the vortex shedding frequency is higher for the finned cylinders than for the bare cylinders, which is again opposite to the single cylinder case, but similar to the previous tandem case. In agreement with the results of Mohany and Ziada [12], strong pre-coincidence resonance occurs for the bare cylinders between V_r = 3.5 and 5. For this spacing ratio, the fins seem to suppress the pre-coincidence resonance and weaken the coincidence resonance which starts near V_r = 6. Increasing the fin density decreases the sound pressure during the coincidence resonance and reduces the lock-in velocity range.

The finned tandem cylinders of type I and type II are able to excite the third mode near the end of the velocity range while the finned cylinders of type III are not for the range of tested velocity. The bare cylinders however did not excite the third acoustic mode, probably because the lock-in resonance of the first mode was so strong that it continued until the maximum attainable flow velocity.

4.2.2. Effect of fins on the wake of tandem cylinders with *S/D*$_e$ = 2. As in the previous cases, velocity measurements were performed on the bare cylinders I and the finned cylinders II at a downstream distance x/De = 2.5 from the downstream cylinder centerline. The reduced velocity was V_r = 2.35, which corresponds to a Reynolds number of Re = 2.7×10^4, and is sufficiently separated from the pre-coincidence resonance range. Figure 9 shows the mean and fluctuation velocity profiles as well as the turbulence intensity distributions. The main differences observed in this case between the finned and the bare cylinder velocity profiles are similar to those observed in the previous case of S/D_e =1.5. It can be concluded that the influence of the fins on the flow, in the absence of resonance effects, is qualitatively the same for S/D_e = 1.5 and S/D_e = 2. This conclusion is supported by the acoustic response recorded before the onset of resonance, which shows that the sound pressure at the vortex shedding

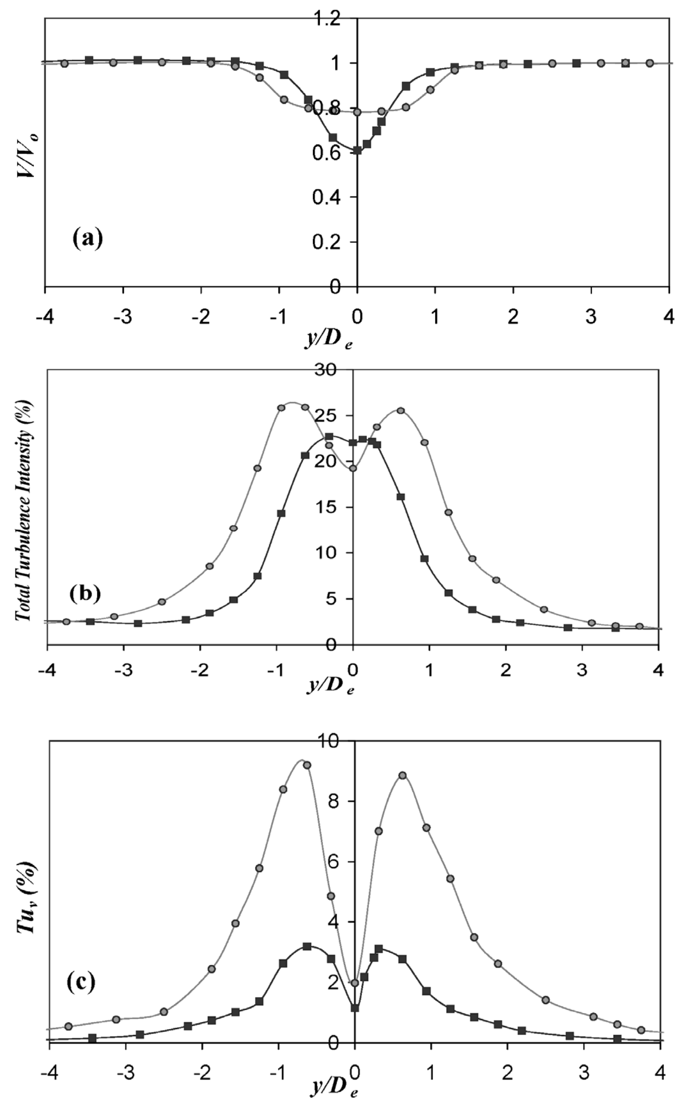

Figure 9. Wake characteristics for *tandem* bare cylinders I and finned cylinders II with S/D_e = 2; (a) mean velocity profiles; (b) total turbulence intensity profiles; (c) fluctuation velocity at the vortex shedding frequency. Measurements performed at x/D_e = 2.5 and V_r = 2.35 (Re = 2.7 x 10^4); —■—, bare cylinder I; —●—, finned cylinder II.

frequency was higher for the finned cylinders in both cases.

4.3. Tandem Cylinders with S/D_e = 3

4.3.1. Effect of fins on the aeroacoustic response of tandem cylinders with S/D_e = 3. For this spacing ratio, vortex shedding is expected to occur in the gap between the cylinders. The interaction between these gap vortices and the downstream cylinder seems to have a strong effect in this case, especially for the pre-coincidence resonance range. As can be seen in Fig. 10(a), at low velocities, the Strouhal number is the

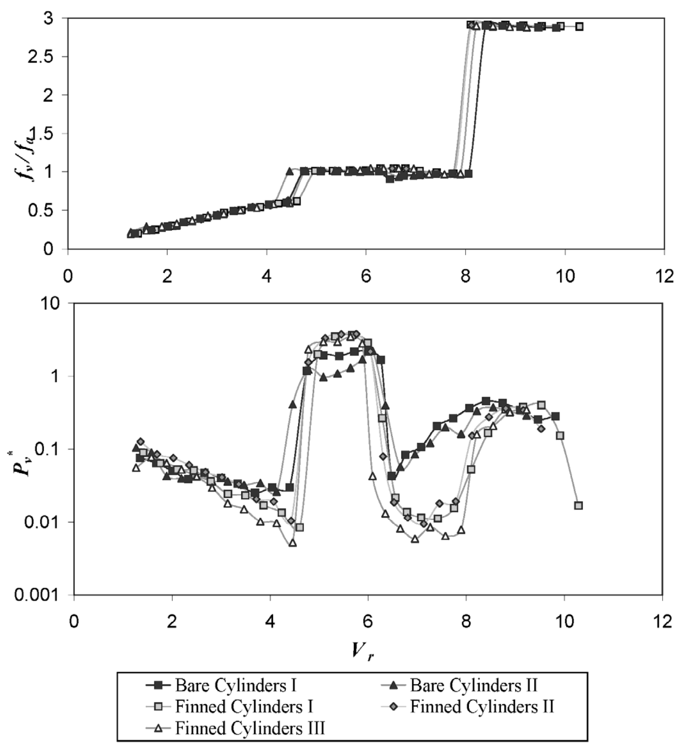

Figure 10. Frequency ratio (f_v/f_a) and the normalized sound pressure (P_v^*) as functions of the reduced velocity (V_r) for bare and finned *tandem* cylinders with S/D_e = 3

same for all cases. The first acoustic mode (f_v/f_a = 1) is excited over two ranges, the pre-coincidence resonance range from V_r = 4.5 to 6.5, and the coincidence resonance range from V_r = 6.5 to 8. The third acoustic mode (f_v/f_a = 3) is thereafter excited at V_r > 8 and its lock-in range is classified as a pre-coincidence resonance range. This is a typical aeroacoustic response of the two tandem cylinders in cross flow as reported by Mohany and Ziada [12,13].

The sound pressure at the vortex shedding frequency at low velocities (V_r < 3) is seen in Fig. 10(b) to be virtually the same for all the cylinders. At slightly higher velocities, i.e. just before the resonance starts, P_v^* for the bare cylinders is higher than those for the finned cylinders. The finned cylinders type III has the lowest value of P_v^* in the velocity range from V_r = 2.8 until the resonance starts.

For the finned cylinders, the first mode excitation at the pre-coincidence resonance range is very strong. The measurements show, contrary to the case of S/D_e = 2, that the sound pressure level is higher in the case of finned cylinders. Despite this higher sound pressure levels in the pre-coincide resonance range, P_v^* for the finned cylinders is significantly lower than that of the bare cylinders in the coincidence resonance range. Since the third mode resonance at V_r > 8 exemplifies a pre-

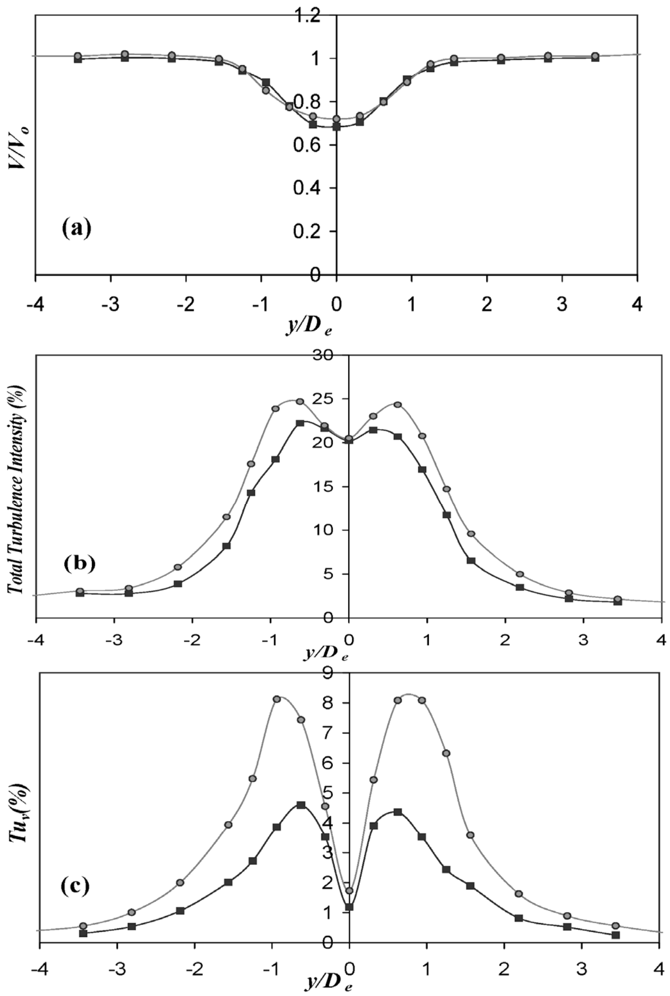

Figure 11. Wake characteristics for *tandem* bare cylinders I and finned cylinders II with S/D_e=3; (a) mean velocity profiles; (b) total turbulence intensity profiles; (c) fluctuation velocity at the vortex shedding frequency. Measurements performed at x/D_e = 2.5 and V_r = 2.35 (Re = 2.7 x 10^4); —■—, bare cylinder I; —●—, finned cylinder II.

coincidence resonance, it is equally excited by both the finned and the bare cylinders. As can be seen in Fig. 10(b), there is no significant difference between P_v^* for the finned and the bare cylinders.

4.3.2. Effect of fins on the wake of tandem cylinders with S/D_e = 3. Velocity measurements for this spacing ratio were performed at a reduced velocity of V_r = 2.35, and as in the previous cases, for the tandem bare cylinders I and the tandem finned cylinders II. The mean velocity and turbulence intensity profiles measured at x/D_e = 2.5 are shown in Fig. 11. The mean velocity profiles for the bare and finned cylinders are almost identical in this case, Fig. 11(a). However, the total turbulence intensity is slightly higher in the case of the finned cylinders and velocity fluctuations at the fundamental vortex shedding component for the tandem finned cylinders is about twice that for the tandem bare cylinders as shown in Figs. 11(b) and 11(c). These results agree with the aeroacoustic response shown in Fig 10, where P_v^* for the finned cylinders is slightly higher than that for the bare cylinders at V_r = 2.35.

Table 2: Strouhal numbers for the single and the tandem cylinders

	Single Cylinder	Tandem Cylinders		
		S/D_e=1.5	S/D_e=2	S/D_e=3
Bare Cylinder Type I	0.198	0.15	0.162	0.145
Finned Cylinder Type I	0.194	0.145	0.154	0.143
Finned Cylinder Type II	0.19	0.143	0.151	0.147
Finned Cylinder Type III	0.194	0.158	0.16	0.145

5. Strouhal Number

The vortex shedding frequency for different cases has been determined from the spectra of the sound pressure measured by the microphone. The Strouhal numbers given here are based on the values of vortex shedding frequencies measured outside the lock-in range. The relationship between the dimensionless frequency (f_v/f_a) and the reduced velocity (V_r) is approximately linear for all the investigated cases. Thus, from the best-fit linear equation for each of the different cases, the Strouhal number values have been determined and are listed in Table 2.

The Strouhal numbers for the finned cylinders are based on the effective diameter D_e. The use of the effective diameter is generally observed to better correlate the Strouhal number data for both the finned and bare cylinders, which agrees with the observation of Mair et al. [23] for single finned cylinders.

The Strouhal number for the single bare cylinder (≈ 0.2) agrees with the Strouhal number values in the literature. The Strouhal number for the tandem bare cylinders also compares well with the Strouhal number reported by Igarashi [5], Lee and Basu [26], Lee and Panagakos [27] and Mohany and Ziada [13].

Table 2 shows that the Strouhal number for single finned cylinders does not change significantly with the change in the fin density. It is observed also that the Strouhal numbers for the single finned cylinders are very slightly smaller than that of the single bare cylinder, which agrees with the observations of Mair et al. [23].

The high fin density seems to affect the Strouhal number in the case of S/D_e = 1.5. Although the Strouhal number is virtually the same for finned cylinders I and II with S/D_e = 1.5, it is higher for the finned cylinders III, which have the highest fin density, as shown in Table 2. The same is also observed in the case of finned cylinders with S/D_e = 2. However, the difference between the Strouhal number of finned cylinders III and that of finned cylinders I and II for this case is smaller than in the case with S/D_e = 1.5.

For the case of S/D_e = 3, the Strouhal numbers for all types of finned cylinders are very close and approximate that of the bare cylinders, Table 2.

6. DISCUSSION

The test results suggest that the effect of fins on vortex shedding and acoustic resonance is quite complex, especially as the flow progresses from the non-resonant regime to the pre-coincidence and coincidence resonance regimes. It turns out that the effect of fins on the wake dynamics depends on many parameters including the fin density, spacing ratio between cylinders, and the predominant flow-acoustic interaction mechanism, i.e. non-resonant, pre-coincidence resonance or coincidence resonance. All these parameters seem to influence how the fins affect the wake dynamics and acoustic resonance.

The introduction of the fins onto the single cylinders caused a significant disruption to the vortex shedding process. This disruption became more pronounced with the increase in the flow velocity or the fin density. The resonance was very weak in the case of the finned cylinders compared to that observed for the bare cylinders. Increasing the fin density reduced the intensity of acoustic resonance.

For the tandem cylinders, the fins were not always disrupting the flow or weakening the vortex shedding process. In fact, the introduction of the fins enhanced the vortex shedding in some cases compared to the corresponding tandem bare cylinders.

For the tandem cylinders with a spacing ratio S/D_e = 2, the introduction of the fins enhanced the vortex shedding significantly before the onset of resonance. However, the fins weakened the acoustic resonance for this spacing ratio. For example, the pre-coincidence resonance did not occur and the coincidence resonance was also weaker than that of the tandem bare cylinders.

When the spacing ratio was decreased to S/D_e = 1.5, the pre-coincidence resonance did not occur for both the bare and the finned cylinders. At this spacing ratio, the fins decreased the sound pressure at the coincidence resonance. The resonance became weaker as the fin density was increased. For the high fin density type III, the lock-in with the first mode was so weak that the vortex shedding was able to emerge out of the lock-in and excite the third mode. However, the fins enhanced the vortex shedding process before the onset of resonance, as in the case of S/D_e = 2.

When the spacing ratio was increased to S/D_e= 3, the first and the third modes were excited. In comparison with the bare cylinders, the level of the first mode resonance at the pre-coincidence range became stronger in the case of finned cylinders. However, it became much weaker at the coincidence resonance. The third mode was excited for the finned and the bare cylinders and the resonance intensity was similar in both cases. An additional observation is that the coincidence resonance became significantly weaker as the spacing ratio is increased from S/D_e=2 to S/D_e=3, while the pre-coincidence resonance became stronger.

7. Summary and Conclusions

The effect of fins on vortex shedding and acoustic resonance for single and two tandem cylinders with three spacing ratios, S/D_e= 1.5, 2, and 3, was investigated for a range of Reynolds number from approximately 10^4 to 10^5. This corresponds to a reduced velocity range up to 10, which is sufficient to investigate the effect of fins on the pre-coincidence and the coincidence resonances for the tandem cylinders.

For the single cylinder case, the introduction of fins is found to reduce the strength of vortex shedding only slightly, but strongly attenuates the radiated sound before the onset and during the lock-in range of the acoustic resonance. This suggests that the impact of fins on the correlation length is stronger than on the velocity fluctuation. These effects become more pronounced with the increase in Reynolds number. The fins also increase the velocity deficit in the single cylinder wake. Increasing the fin density decreases the sound pressure during acoustic resonance.

In agreement with the work of Mohany and Ziada [12, 13], the acoustic resonance for tandem cylinders (bare and finned) is generally stronger and the lock-in range is wider than those for single cylinders. However, the effect of fins on the wake and the aeroacoustic response of the tandem cylinders is rather complex and depends on the spacing ratio, the fin density and the nature of the flow-sound interaction mechanism. The following is a summary of the effect of fins on the wake and sound generation of two tandem cylinders, in comparison with the characteristics of tandem bare cylinders.

In contrast to the single cylinder case, the fins enhance the vortex shedding process at off-resonant conditions, except for the large spacing case (S/D_e = 3) where this effect seems to be reversed at high Reynolds numbers ($Re > 4\text{x}10^4$). Another feature which contradicts the observation of the single cylinder case is that the fins widen the wake and reduce the mean velocity deficit for the tandem cylinders.

Regarding the excitation of acoustic resonance for the tandem cylinders, the fins are found to promote the onset of coincidence resonance, but increasing the fin density weakens this coincidence resonance drastically, which results in lower sound pressure and narrower lock-in velocity range. The fins also appear to suppress the pre-coincidence resonance for tandem cylinders with small spacing ratios (S/D_e = 1.5 and 2), but do not influence it for larger spacing ratios (S/D_e = 3).

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