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PARAMETRIC INVESTIGATION OF THE FLOW-EXCITED ACOUSTIC RESONANCE FROM MULTIPLE IN-LINE CYLINDERS IN CROSS-FLOW

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ABSTRACT

In this paper, the flow-excited acoustic resonance of an in-line row of cylinders ranging from one to five is investigated. Cylinders of three different diameters of 12.7 mm, 19.1 mm, and 25.4 mm are tested in cross flow with flow speeds up to 160 m/s. Two different tube lengths of 76.2 mm and 127 mm are used to investigate the effect of the cylinder's aspect ratio at a given diameter on the excitation mechanism of acoustic resonance. A fixed spacing ratio of $L/D = 2$ is used for all cases. For more than one cylinder of the larger diameter, the self-excitation of resonance occurs at two discrete flow velocity regions that are generally wider than the case of a single cylinder. A larger diameter does not only trigger the excitation of the pre-coincidence resonance region, but also increases the normalized acoustic pressure of this pre-coincidence resonance. On the contrary, the cylinder's aspect ratio does not have a similar effect on the pre-coincidence and coincidence resonance regions. Therefore, it is important that the effect of diameter should be included in formulas predicting the occurrence of resonance for in-line tube bundles. In addition, the Strouhal number related to the coincidence resonance decreases with the increase in the number of cylinders. The coincidence resonance is related to the vortex shedding in the wake of the last cylinder, while the pre-coincidence resonance is related to the shear layer in the gap between successive cylinders.

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NOMENCLATURE

- D Cylinder diameter
- f Frequency
- f_a Frequency of the first acoustic cross-mode
- f_v Vortex shedding frequency
- L Center to center spacing
- M Mach number
- P Acoustic pressure
- P^* Normalized acoustic pressure
- St Strouhal Number
- SPL Sound pressure level
- U Free-stream flow velocity
- U_r Reduced acoustic velocity
- W cylinder span-wise length
- ρ Density

INTRODUCTION

The occurrence of acoustic resonance in tube bundles due to fluid flow is a major concern in many engineering applications. High sound pressure levels have been attributed to flow-excited acoustic resonance inside heat exchangers [1], cascades of blades [2], piping systems [3], flow controllers [4], and many other industrial applications [5]. The flow-excited acoustic resonance results in acoustic pressures that may exceed the dynamic head of the mean flow, causing unsafe levels of noise and damage to equipment. Detailed investigations of many aspects of the

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phenomenon of flow-excited acoustic resonance have been presented in literature in the past few years. However, the complex nature of the interaction between the flow and sound fields in different tube arrangements still needs further understanding.

When tube arrays exist in a ducted flow field, periodic vortex shedding occurs due to boundary layer separation and rolling in the near field. If the vortices are shed at a frequency that coincides with an acoustic cross-mode of the duct, the vorticity field can act as a sound source. The feed-back provided by the acoustic particle velocity in the sound field enhances the vortex shedding. This completes a cycle that leads to self-sustained acoustic resonance. Flow-excited acoustic resonance is a complex phenomenon with dependency on many geometric and dynamic variables. Blevins [6] described the modulating effect of sound from an external source on the frequency of vortex shedding. Blevins [6] also proposed that self-induced sound can lead to persistent and intense acoustic resonance for a single cylinder as well as arrays of cylinders. To identify the source of the vorticity-shedding excitation in in-line cylinder arrays, Ziada and Oengören [7] performed extensive measurements in closely packed in-line tube arrays. They suggested that a jet instability in the tube lanes is found to be the vorticity-shedding excitation. Fitzpatrick [8] reviewed the damping criteria used to predict the self-excitation of noise in tube bundles. The damping criteria are formulated to depend mainly on the spacing to diameter ratio of the bundle and its configuration. Similar approach is used to predict the frequency of the resonance excitation. Weaver et al. [9] suggested a dependency of the Strouhal number on the spacing ratio of the cylinders for several arrangements of tube bundles.

To further understand the complex nature of the flow-sound interaction in tube bundles, the simple case of two tandem cylinders in cross-flow has been investigated by Mohany [10]. In a series of papers, Mohany and Ziada thoroughly investigated the self-excited acoustic resonance of tandem cylinders of different spacing ratios in a duct [11–14]. They observed that when two cylinders are closely spaced, resonance occurs at two different ranges of flow velocities. A coincidence between the vortex shedding frequency and the acoustic mode frequency results in a resonant noise. More interestingly, resonance is also observed at much lower flow velocities than necessary for a coincidence. This earlier resonance, referred to as the *pre-coincidence resonance* occurred when the acoustic mode frequency was significantly higher than the vortex shedding frequency in the wake. Extending their investigations in a following study [12], they further investigated the nature of the two resonance regions. They showed that the resonance in the case of two cylinders occurs over a wider lock-in region and produces higher unsteady pressure levels, approaching the case of the in-line tube bundles. They suggested for the first time that the earlier resonance is the main contributor to resonance in in-line tube bundles. During the experiments of Mohany and Ziada [11] of self-excited acoustic resonance in two tandem cylinders, the pre-coincidence resonance did not occur systemically at various cases of different diameters nor aspect ratios. Pre-coincidence resonance was not observed for cylinders of a small diameter of $D = 12.7$ mm.

Mohany and Ziada [13] later provided experimental evidence that, for self-excited acoustic resonance in two tandem cylinders, the two different lock-in regions are of different nature. The lift force acting on the two cylinders remains identical to the non-resonant cases for the coincidence region. However, the lift force changes significantly during the pre-coincidence resonance. The phase shift of the lift coefficient and vortex shedding behind the upstream and downstream cylinders is much lower for the coincidence resonance than the pre-coincidence resonance. Moreover, the upstream and downstream cylinders are shedding vortices in-phase for the coincidence resonance. On the other hand, for the pre-coincidence resonance, cylinders shed vortices that are 90° out of phase. A numerical study of the coincidence and pre-coincidence resonance sources was carried out to identify the acoustic energy sources around the cylinders [14]. For the pre-coincidence resonance, the acoustic energy source is located in the gap between the cylinders. Therefore, this earlier resonance is attributed to the instability of the shear layer in the gab between the two cylinders. On the contrary, the acoustic energy source for the coincidence resonance is in the wake of the downstream cylinder, where a shedding wake is allowed to evolve. The most significant conclusion of the study of Mohany and Ziada [12] is that the diameter of the cylinders, rather than the spacing ratio, has a significant effect on the nature and lock-in region of pre-coincidence resonance.

In an extensive investigations of the characteristics of flow around in-line cylinders, Igarashi [15] investigated the flow characteristics around two cylinders in tandem at different Reynolds numbers and spacing ratios. Igarashi [15] observed that a change of flow structures around the cylinders takes place at a specific spacing ratio and a specific Reynolds number range. In a following study, Igarashi and Suzuki [16] investigated the flow around three in-line cylinders. For this case, they reported hysteresis in a transition between the high Strouhal number for close proximity, and the much lower Strouhal number for cases where the vortices between the cylinders are allowed to attach because of the higher spacing to diameter ratio.

In a later investigation of the case of four cylinders, Igarashi [17] was able to identify two categories of flow patterns. The first category of patterns occurs at lower spacing ratios where no cylinder except the most downstream one has a vortex shedding, causing the row of cylinders with stagnant entrapped fluid to act as a continuous body. In the other category of patterns, the flow behind all cylinders fluctuates and sheds vortices at the same frequency. Hysteresis is detected between the two categories while increasing or decreasing Reynolds number. Hetz et al. [18] presented a detailed examination of the flow around five in-line cylinders. They argued that the different patterns of flow around in-line rows of cylinders can be explained by the in-

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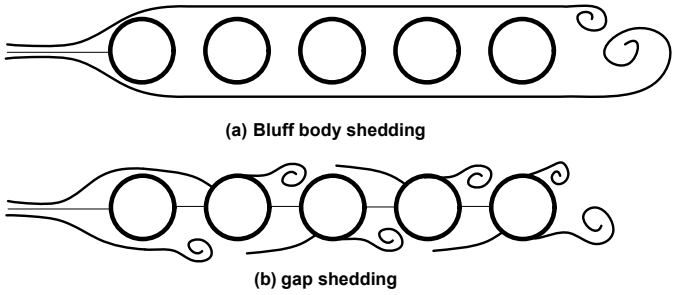


FIGURE 1. A SCHEMATIC OF DIFFERENT FLOW PERIODIC PATTERNS AROUND AN IN-LINE ROW OF FIVE CYLINDERS

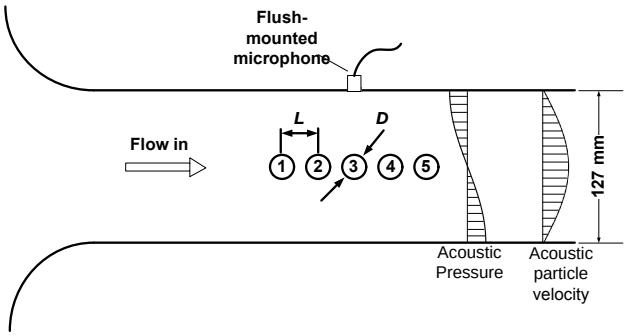


FIGURE 2. A SCHEMATIC OF THE EXPERIMENTAL SETUP

teraction of distinct forms of organized flow patterns as shown in figure 1: (a) The row of cylinders may act as one long bluff body, causing vortex shedding downstream of the entire system in the *bluff-body shedding* pattern. (b) The second possible pattern of oscillation involves the formation of vortices which shed alternatively through the gaps. The corresponding pattern of antisymmetric, alternating oscillations is referred to as *gap shedding* hereafter. By modifying the geometry of the in-line cylinder bundle to allow different patterns separately, they were able to show that different patterns are responsible for flow periodicities that can coexist, switch at certain Reynolds number, or go through a hysteresis cycle. To sustain a high sound pressure level of a self-excited resonance, a feed-back cycle is needed to increase the efficiency of energy exchange between the periodic oscillations of hydrodynamic nature, and fluid particle oscillations of acoustic nature. In a case of resonance, Mohany and Ziada [19] reported that the hydrodynamic lift force on the cylinder is in-phase with the acoustic pressure. Therefore, it follows that the frequency of the hydrodynamic oscillations is the same as the acoustic oscillations in resonance conditions. However, the two types of oscillations should be independent at off-resonance conditions. The patterns of bluff-body shedding and gap shedding are antisymmetric hydrodynamic patterns that are able to sustain energy to the acoustic field, which is inherently antisymmetric.

The work presented in this paper is motivated by the need to investigate the nature of the phenomenon of pre-coincidence acoustic resonance observed in some cases of the experimental work by Mohany and Ziada [11,12] and extent their work to multiple cylinders in cross-flow. This earlier-than-expected region of resonance exhibits characteristics similar to those of an in-line tube bundle. Moreover, this work aims at clarifying the effect of the cylinder diameter and its aspect ratio on the excitation mechanism of both the coincidence and the pre-coincidence acoustic resonance. Investigating the flow-sound interaction mechanism from these simplified cases of in-line cylinders in cross-flow will contribute to the understanding of the more complex flow-sound interaction mechanisms in tube bundles.

EXPERIMENTAL SETUP

The experiments are performed in an open loop wind tunnel. A schematic drawing of the experimental setup is shown in figure 2. The dimensions of the test section are carefully selected to ensure coincidence between the frequency of vortex shedding and the frequency of the first acoustic resonance mode in the transverse direction. The wind tunnel test section has a height of 25.4 cm. The first acoustic cross-mode, illustrated in figure 2, has a resonance frequency of 670 Hz. The inlet section of the apparatus is fitted to a bellmouth to ensure steady uniform velocity profile within 1% of the mean value at the measurement section. The distance from the inlet edge to the center of the most upstream cylinder is 0.305 m. A diffuser with a length of 0.625 m has the same tunnel height of 0.254 m, uniformly expanding in the width direction to a width of 0.508 m at the blower inlet connection. Two different test section widths of W = 76.2 mm and 127 mm to allow testing cylinders of different aspect ratios.

To test the acoustic resonance occurrence and characteristics, cylinders are attached in an in-line configurations in cross-flow. A single cylinder, and in-line row of two, three, four, and five cylinders of the same diameter are tested in cross-flow. A fixed spacing ratio is used so that, for all cases, the centres of the cylinders are separated by $L = 2\ D$. The numbers on the cylinders in figure 2 indicate the order of their attachment to increase the number of cylinders. Three different diameters are separately tested, namely 12.7 mm, 19.1 mm, and 25.4 mm.

The acoustic pressure of the acoustic standing wave is measured at the acoustic pressure anti-node using a ¼ inch flush mounted pressure microphone at the top wall of the test section. Arafa et al. [20] observed that the location of the maximum acoustic pressure on the channel walls is located downstream of the attached cylinder. Therefore, the microphone is mounted at a distance of 4D downstream from the center of the most-upstream

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cylinder in all configurations, where L is the center to center spacing. Acoustic pressure is recorded at flow velocities up to 165 m/s. The pressure values are recorded with a sampling rate of 11.025 kHz for 30 seconds. The acoustic pressure measurements are transformed into the frequency domain by taking an average of 30 ensembles to analyse the frequency spectrum of the acoustic wave with a precision of 1 Hz and up to 5.5 kHz. The root mean square of the sound pressure level at resonant frequency at each free-stream flow velocity is then extracted.

AEROACOUSTIC RESPONSE OF A ROW OF IN-LINE CYLINDERS

In this section, the acoustic resonance of a row of in-line cylinders is discussed to provide more insight into the nature of excitation responsible for flow-excited acoustic resonance. Results in this section aim to highlight the effect of the cylinder diameter on the acoustic resonance. A discussion of the characteristics of pre-coincidence and coincidence lock-in regions is provided.

The aeroacoustic response of a bundle of cylinders in cross-flow is studied as a relationship between the normalized acoustic pressure P^* and the normalized flow velocity, U_r. P^* is defined in equation 1 as

$$P^* = \frac{P}{0.5\rho U^2 M} \tag{1}$$

where P is the acoustic pressure, U is the free-stream flow velocity, ρ is the fluid density, and M is the flow Mach number. This normalized form is derived from the theory of aeroacoustic sound [11]. The normalized flow velocity U_r is defined in equation 2 as:

$$U_r = \frac{U}{f_a D} \tag{2}$$

where f_a is the frequency of the first acoustic cross-mode of the duct and D is the cylinder diameter. The frequency of periodic phenomena is shown in the form of Strouhal numbers St, defined in equation 3.

$$St = \frac{f_v D}{U} \tag{3}$$

Figure 3 shows the aeroacoustic response of the cases of selected configurations. Figure 3A shows the spectra of the sound pressure level SPL at frequencies up to 1 kHz for one cylinder with D = 25.4 mm. A peak in the spectra is detected at every frequency and is found to have a Strouhal number of St = 0.2

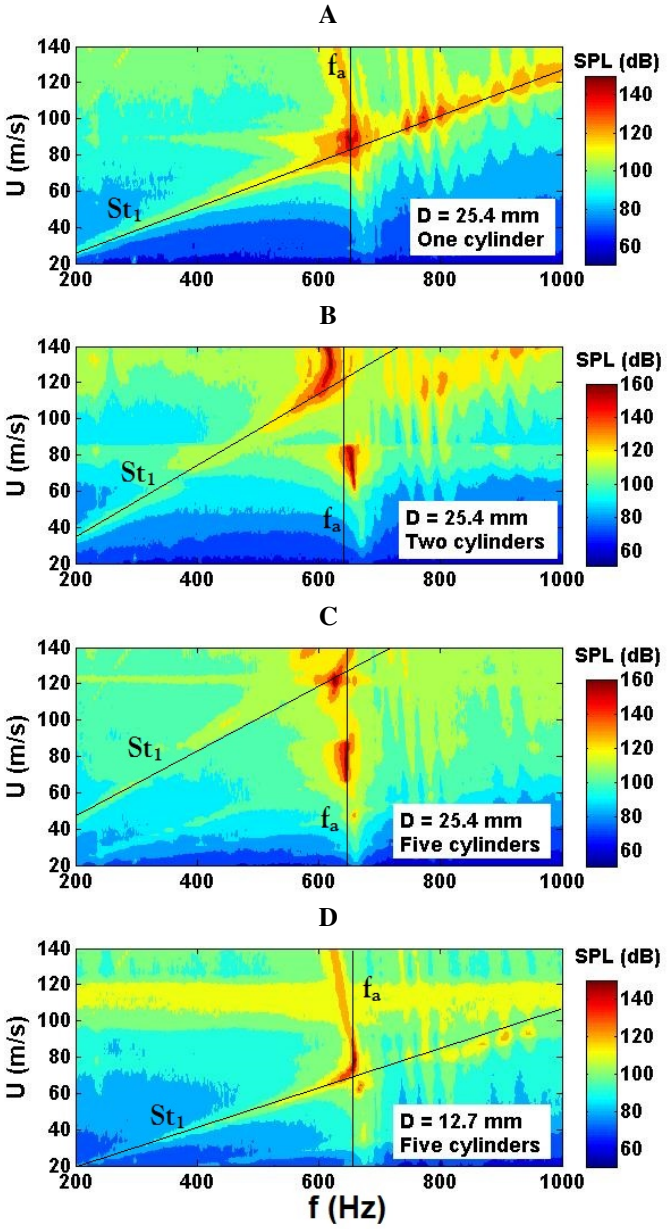


FIGURE 3. ACOUSTIC RESPONSE OF AN IN-LINE ROW OF CYLINDERS IN CROSS FLOW WITH A SPACING RATIO OF L/D = 2. **A.** D = 25.4 MM, ONE CYLINDER. **B.** D = 25.4 MM, TWO CYLINDERS. **C.** D = 25.4 MM, FIVE CYLINDERS. **C.** D = 12.7 MM, FIVE CYLINDERS

indicating that it is a result of periodic vortex shedding downstream of the cylinder. At the coincidence of the vortex shedding frequency with the acoustic cross-mode frequency, a resonance of high pressure level reaching 153 dB is observed. Further increase in air velocity causes the sound pressure level to decrease

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as the frequency of vortex shedding is shifted away from the first acoustic cross mode frequency.

For the case of two tandem cylinders of the same diameter with a spacing ratio of $L/D = 2$, Figure 3B shows a different behaviour. While the frequency of vortex shedding is lower at each flow velocity, a region of resonance occurs at velocities where the frequency of vortex shedding is much lower than the first acoustic cross-mode frequency. At 80 m/s, the frequency of vortex shedding is nearly 400 Hz, while a resonance of high sound pressure level of 156 dB is detected. A further increase in air velocity causes this resonance region to end and the sound pressure level to decrease. At higher velocities around 135 m/s, another lock-in region prevails at the coincidence of vortex shedding and the first acoustic cross-mode, resulting in high sound pressure level.

Increasing the number of cylinders, a similar behaviour is observed. For the case of five cylinders shown in figure 3C, the same two resonance regions are detected and high sound pressure levels are observed at flow velocities of 80 m/s and 140 m/s. However, the Strouhal number of the vortex shedding decreases with increasing the number of cylinders. The cases of three and four cylinders of $D = 25.4$ mm gave a response similar to that in figure 3C. An important aspect of figure 3C is the detection of two different periodic phenomena, with a linear frequency dependence on the flow velocity. The one with the higher frequency has a Strouhal number $St = 0.24$, while the other one has $St = 0.12$. The two different regions of resonance occur when each of these periodic phenomena coincides with the first acoustic cross-mode frequency.

Figure 3D shows the aeroacoustic response of five cylinders of a smaller diameter, $D = 12.7$ mm, at the same spacing ratio $L/D = 2$ in cross-flow. The smaller diameter in this case causes the frequency at each velocity to be higher. The Strouhal number for this case is found to be similar to the lower Strouhal number in the case of five cylinders with $D = 25.4$ mm, $St = 0.125$. However, a resonance with the characteristics of the pre-coincidence resonance is not detected. This is also observed for all cases with the diameter of $D = 12.7$ mm. It can be observed in figure 3 that the resonance decreases slightly with the increase in flow velocity because the effect of the fluid added mass is expected to change the resonance frequency, as discussed by Mohany and Ziada [13, 19]. In addition, an increase in flow velocities is expected to change the convection velocity, which in turn will affect the resonance frequency.

Figure 4 compares the acoustic response of a single cylinder to a row of four cylinders with a spacing ratio $L/D = 2$ for the diameter $D = 2.54$ mm. The abscissa of the figure is the ratio of the shedding frequency f_v to the first acoustic mode frequency f_a, which is equivalent to the multiplication of Strouhal number by the normalized flow velocity, $St.U_r$. Figure 4 shows the region of pre-coincidence which occurs before the ratio f_v/f_a reaches 1.0, and is not observed for the single cylinder case. The coincidence

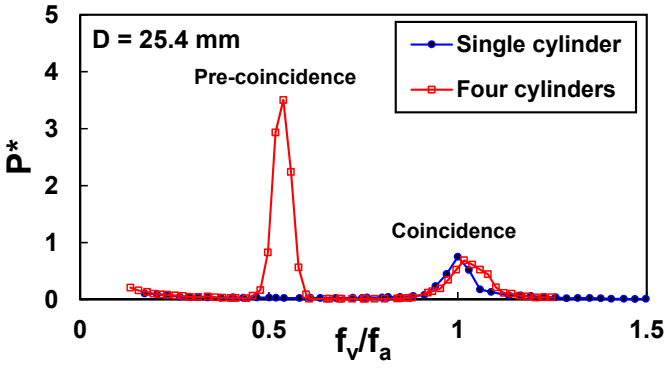


FIGURE 4. COMPARISON OF THE AEROACOUSTIC RESPONSE OF A SINGLE CYLINDER WITH THAT OF FOUR IN-LINE CYLINDERS. $L/D = 2$ AND $D = 25.4$ MM

resonance occurs for both cases at $f_v/f_a = 1.0$.

Figures 5 and 6 show the normalized pressure and frequency of the resonance peaks for the same selected cases shown in figure 3. The case of the single cylinder is shown in figure 5A. The lock-in region occurs at the coincidence of the vortex shedding frequency and the first acoustic cross-mode frequency. The pressure increases and P^* reaches 0.9 nearly at $U_r = 5$. When two tandem cylinders are attached, figure 5B shows that in the range of U_r between 3.5 and 5.0, the frequency of the peaks jump to a resonance at the first acoustic cross-mode frequency and the normalized pressure P^* reaches 3.5. As the normalized speed increases, another lock-in region is found in the range of U_r between 6.5 and 9, where the normalized pressure reaches P^* of 1. A further increase in the number of cylinders causes a similar behaviour with a shift in the flow velocity range of the coincidence resonance. In figure 6A, the first lock-in region occurs nearly at the same range as in figure 5B, with P^* increasing to 4.3. However, the range of coincidence lock-in region is shifted to higher flow velocities between U_r of 9 to 11, which is out of the equipment operating range. Figure 6B shows the response of five cylinders of a smaller diameter, $D = 12.7$ mm, at the same spacing ratio of $L/D = 2$. Figure 6B shows that the pre-coincidence lock-in region did not take place. Only the coincidence resonance is detected. Moreover, the flow velocity range of this coincidence is the same as the one for five cylinders of a larger diameter, and the normalized pressure is around $P^* = 1.3$.

Figure 7 shows the sound pressure level at various flow velocities for a row of two tandem cylinders of $L/D = 2$, a row of five tandem cylinders with $L/D = 2$, and the case of an in-line tube bundle with spacing rations of $L/D = 2.1$ in the horizontal direction, and $T/D = 2.5$ in the vertical direction from the study of Ziada and Oengören [21]. The figure shows that the three cases show a good agreement in the resonance region at

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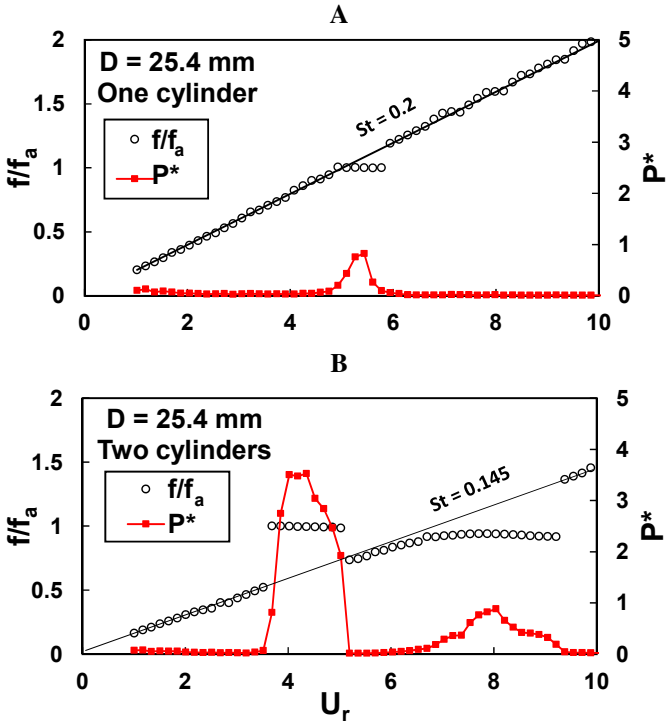


FIGURE 5. NORMALIZED PRESSURE AND FREQUENCY OF A ROW OF IN-LINE CYLINDERS IN CROSS FLOW WITH A SPACING RATIO OF $L/D = 2$. **A.** $D = 25.4$ MM, ONE CYLINDER. **B.** $D = 25.4$ MM, TWO CYLINDERS

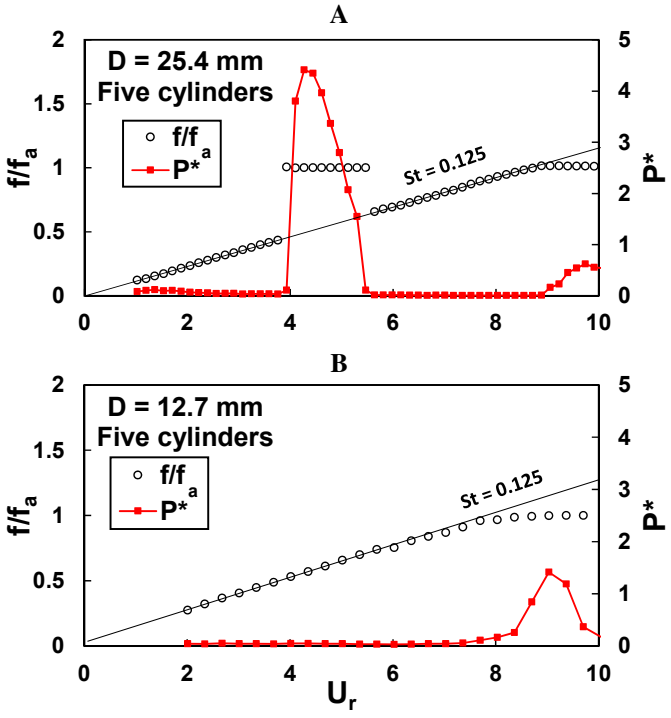


FIGURE 6. NORMALIZED PRESSURE AND FREQUENCY OF A ROW OF IN-LINE CYLINDERS IN CROSS FLOW WITH A SPACING RATIO OF $L/D = 2$. **A.** $D = 25.4$ MM, FIVE CYLINDERS. **B.** $D = 12.7$ MM, FIVE CYLINDERS

U_r between 4 and 6. The lock-in region is wider for the in-line tube bundle. The increase in the number of tubes from two to five caused a wider lock-in region. It can be expected that the addition of other rows is responsible for the wider lock-in region for the tube bundle case. However, the reasonable agreement suggests that the characteristics of the pre-coincidence lock-in region are more relevant to the resonance in in-line tube bundles than the coincidence region.

Figure 8 shows the normalized pressure dependency on the reduced flow velocity for an in-line row of four cylinders of three different diameters. In the range of pre-coincidence, the increase of diameter has a significant effect on the pressure of the resulting resonance. For the smallest diameter, $D = 12.7$ mm, no pre-coincidence resonance is observed. Increasing the diameter to $D = 19.1$ mm, pre-coincidence resonance occurred and the normalized pressure reached a maximum of $P^* = 1.1$. A further increase in the diameter caused a further increase in the normalized pressure to $P^* = 4.9$. For the coincidence resonance, the normalized pressure did not change as much. However, the diameter increase caused the maximum pressure of the coincidence resonance to occur at a higher reduced flow velocity of 8.9 for $D = 25.4$ mm rather than 8.4 for $D = 12.7$ mm.

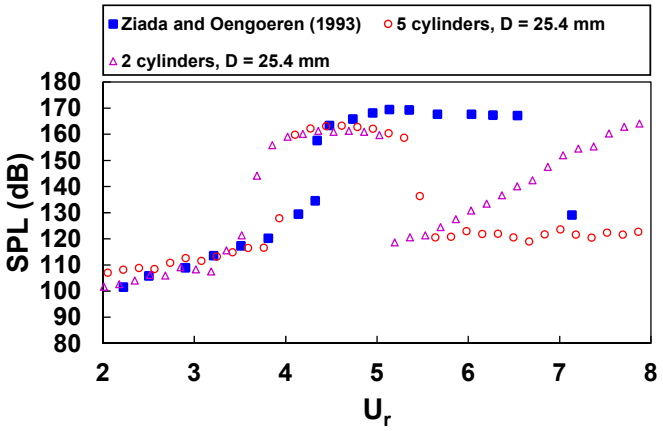


FIGURE 7. SOUND PRESSURE LEVEL IN THE CASES OF TWO AND FIVE CYLINDERS OF $D = 25.4$ MM AND $L/D = 2$, COMPARED WITH THAT OF AN IN-LINE TUBE BUNDLE WITH $L/D = 2.1$ [21]

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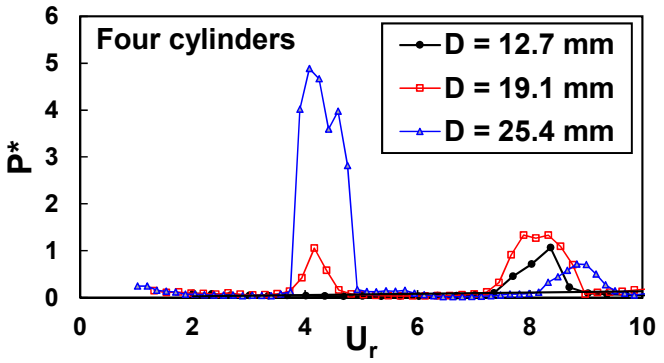


FIGURE 8. NORMALIZED PRESSURE FOR AN IN-LINE ROW OF FOUR CYLINDERS OF DIFFERENT DIAMETERS

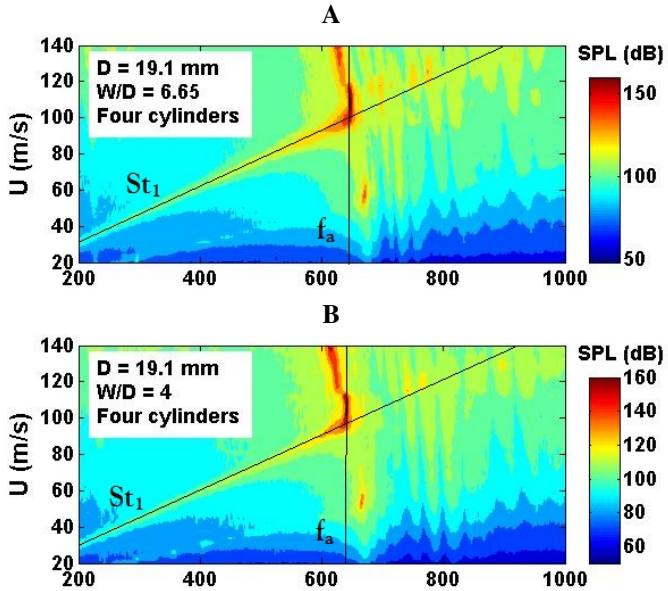


FIGURE 9. PRESSURE SPECTRA AT DIFFERENT FLOW VELOCITY FOR FOUR CYLINDERS OF D = 19.1 MM AND TWO ASPECT RATIOS **A.** W/D = 6.65 AND **B.** W/D = 4

Figure 9 shows the spectra of the sound pressure level for an in-line row of four cylinders of diameter D = 19.7 mm with two different aspect ratios, W/D = 6.65 and 4.00. The two cases did not show significant differences in the response. Pre-coincidence resonance occurred around U = 50 m/s, while coincidence resonance occurred at a velocity of U = 95 m/s for both cases.

The normalized pressure of the pressure peak for the same cases in figure 9 at each velocity is shown in figure 10. For the pre-coincidence resonance, the different aspect ratios reach a nearly equal maximum normalized pressure of 1.1. At the coincidence range, the two cases reaches their maximum normal-

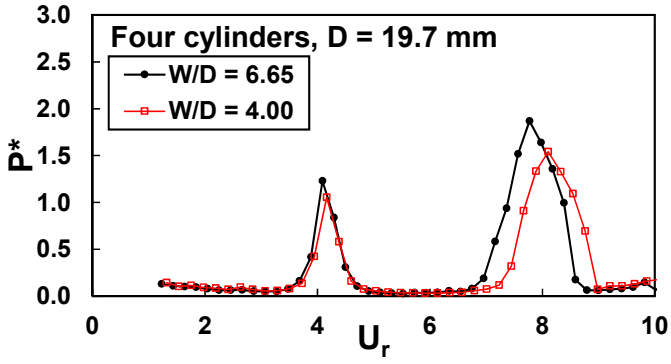


FIGURE 10. NORMALIZED PRESSURE FOR FOUR CYLINDERS OF D = 19.1 MM AND TWO ASPECT RATIOS W/D = 6.65 AND W/D = 4

ized pressure at U_r = 7.77, and 8.32 for W/D of 6.65 and 4.00 respectively.

From these results, it is shown that the pre-coincidence resonance can be observed not only in the case of two tandem cylinders, but also for higher number of in-line cylinders. Although the spacing ratio L/D is kept constant for all cases, the behaviour of the pre-coincidence resonance was significantly affected by the increase in cylinder diameter. Pre-coincidence resonance is not detected for cylinders of small diameters, D = 12.7 mm in our experiments. An increase in diameter to 19.7 mm resulted in the existence of the pre-coincidence resonance, and a further increase to 25.4 mm caused a significant increase to its normalized pressure. The cylinder's aspect ratio does not show the same effect on the acoustic response in the experiments.

STROUHAL NUMBER IN AN IN-LINE ROW OF CYLINDERS

In this section, the acoustic response of an in-line row of cylinders is discussed in terms of the Strouhal number. Results are presented to compare the Strouhal number of the peaks present in the spectra of the acoustic pressure to Strouhal numbers of known periodicities in flow around a row of in-line tubes.

Figure 11 shows the spectra of the acoustic pressure at different flow speeds in the case of two cylinders and five cylinders. In the case of two cylinders, a peak in the spectra is detected at a frequency that increases with increasing velocities, which suggests that this peak is related to a phenomena of hydrodynamic nature. A peak is observed at 670 Hz. The frequency of this peak is nearly constant, suggesting an acoustic nature. The frequency of this peak is in close agreement with the frequency of the first acoustic cross-mode of the duct, whose pressure and particle velocity distributions are shown in figure 2. The acoustic mode peak is barely detected at the flow velocity of 20 m/s. As the speed increases, it slightly increases due to the increase of exci-

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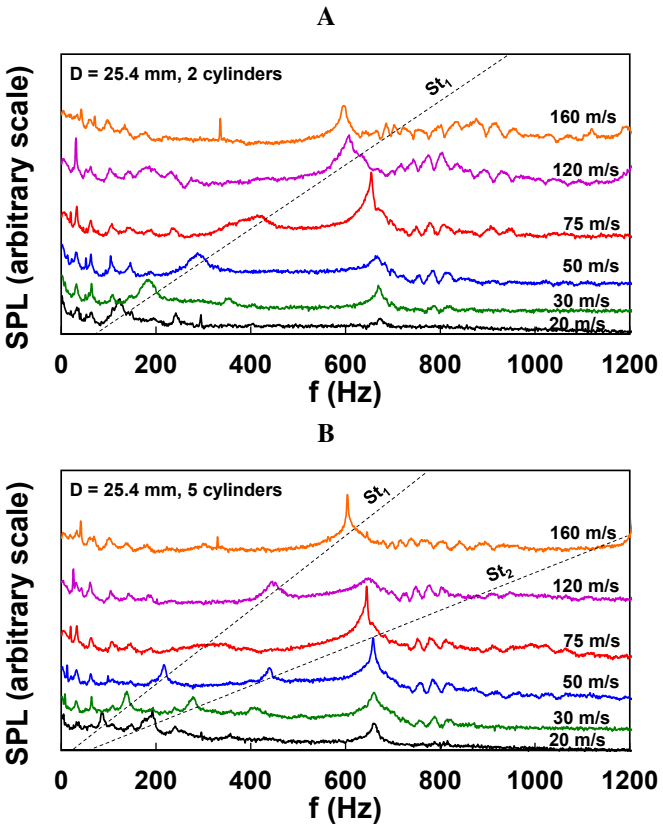


FIGURE 11. **A.** SPECTRA OF THE PRESSURE SIGNAL AT VARIOUS FLOW VELOCITIES FOR THE CASES OF **A.** TWO CYLINDERS OF D = 25.4 MM, AND **B.** FIVE CYLINDERS OF D = 25.4 MM

tation energy provided by the turbulent buffeting in the duct. At 85 m/s, the frequency of the hydrodynamic oscillations reaches 670 Hz. The peaks of hydrodynamic nature occur at a Strohal number of St = 0.145, in good agreement to the Strouhal number of 0.15 reported by Igarashi [15] for the case of two tandem cylinders shedding vortices. This flow pattern has similarities to pattern (a) in figure 1. The observation of resonance is first encountered at U = 75 m/s, where a peak of acoustic resonance is detected at f = 670 Hz, with a significantly high sound pressure level of P = 2300 Pa, equivalent to SPL = 161 dB. No peak of hydrodynamic nature that can excite this resonance is detected at the spectra of pressure for lower velocities. Increasing the flow velocity further to U = 120 m/s, another resonance is detected with P = 3641 Pa, equivalent to SPL = 165 dB. This latter resonance is similar to the one observed for one cylinder, in terms of being at the coincidence of the hydrodynamic Strouhal number, St = 0.145, and the acoustic mode frequency, f = 670 Hz.

The second case shown in figure 11 is the spectra for five in-line cylinders. In this case, the spectra at low velocities of U = 20, 30, and 50 m/s has two pressure peaks at two different frequencies, both increasing as the flow velocity increases. These two periodicities are detected at St = 0.12, and St = 0.23. Pressure peaks are detected at U = 75 m/s and U = 160 m/s, indicating that the two periodic oscillation frequencies are able to excite a sustainable self-excited resonance regions. The sound pressure levels reached 163 dB for the pre-coincidence and 166 dB for the coincidence resonance, whereas the normalised pressure is P^* = 4.34 for the pre-coincidence resonance and P^* = 0.62 for the coincidence resonance. Similar behaviour is observed for the cases of three and four cylinders at D = 25.4 mm, where two hydrodynamic periodic peaks are detected.

The ratio of the two Strouhal numbers are close to 2.0, which may suggest they are harmonics of the same hydrodynamic periodic phenomena. However, Hetz el al. [18] reported two different Strouhal numbers for periodic oscillations of two different hydrodynamic natures; St = 0.124 for bluff-body oscillations (pattern (a) in figure 1) and St = 0.232 for gap shedding oscillations (pattern (b) in figure 1). Figure 12 shows a comparison of the Strouhal numbers for the two hydrodynamic periodic oscillations at different Reynolds numbers for different diameters. The Strouhal numbers reported by Hetz et al. are reported for L/D = 1.8, and for a cylinder diameter of 76.2 mm, but they are still in acceptable agreement with Strouhal numbers for the current spacing ratio of L/D = 2.0. The higher Strouhal number St_2, apparently responsible for the pre-coincidence resonance excitation agrees well with the higher strouhal number observed by Hetz et al. [18]. Morover, an agreement is found between St_1 and the Strouhal numbers of around 0.125, which Hetz et al. [18] attributed to the vortex shedding in the wake of the cylinders when they behave as one bluff-body.

The effect of the number of cylinders on the Strouhal number of the pressure peaks detected in the spectra is shown in figure 13. Strouhal numbers responsible for the coincidence resonance, St_1, decreases with an increase in the number of cylinders. A strouhal number of about 0.2 is detected for a single cylinder for all diameters. The diameter has no significant effect on the Strouhal number St_1 for all numbers of tubes. A good agreement of this Strouhal number with those reported for the same number of tubes in the studies discussed above is shown in figure 13. As this Strouhal number is responsible for excitation of resonance in the coincidence range, patterns of bluff-body vortex shedding reported by Hetz el al., Igarashi, Igarashi and Suzuki [15–18] are thought to be responsible for the coincidence resonance. This can explain why the normalized acoustic pressure and Strouhal numbers are not significantly affected by the change in diameter, as the flow in this pattern sheds after the row of cylinders as it is a bluff-body, and the source of the excitation is downstream of the most downstream cylinder, where the vortices have enough space to grow regardless of the cylinder diameter. For the case of two cylinders, this finding agrees with the results of the numerical simulations performed by Mohany and Ziada [14].

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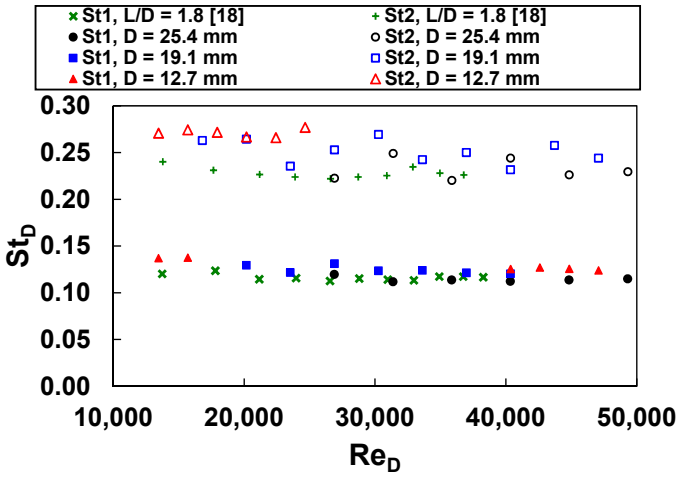


FIGURE 12. EFFECT OF REYNOLDS NUMBER ON STROUHAL NUMBER OF PEAKS OF HYDRODYNAMIC PERIODIC OSCILLATIONS IN THE SPECTRA OF PRESSURE FOR DIFFERENT DIAMETERS

The Strouhal number responsible for excitation of the pre-coincidence resonance, St_2 is not reported for the case of two cylinders and no peak is detected in the spectra. However, the excitation occurs for two cylinders and for a higher number of cylinders. The increase in the number of cylinders causes the peak to become visible in the spectra, specially at higher velocities. The peak is easily identified in the case of five cylinders, as previously shown in figure 11. Figure 13 shows that the number of cylinders does not affect the value of Strouhal number St_2 significantly. However, the dependence of this value on diameter is more pronounced. The Strouhal number of this periodic oscillations is close to the reported value of 0.24 by Hetz et al. at D = 76.2 mm. Increasing the cylinder diameter causes a slight decrease of Strouhal number. The gap shedding flow pattern is responsible for Strouhal numbers close to this value. This agrees with the findings of the numerical simulations of Mohany and Ziada [14] that the source of net acoustic energy is located between the cylinders.

For the case of two cylinders, the occurrence of the pre-coincidence resonance within the same region as that of a higher number of cylinders suggests that the excitation arises from a source of the same nature. A periodic oscillation of this Strouhal number is not detected in the pressure spectra or reported in literature. This might suggest that this pattern of flow is weaker than other flow structures, or that it is a mode of flow that does not inherently exist at some conditions. In both cases, this pattern is still able to engage in a feed-back cycle when its frequency coincidence occurs and it gains strength that can self-sustain a resonance.

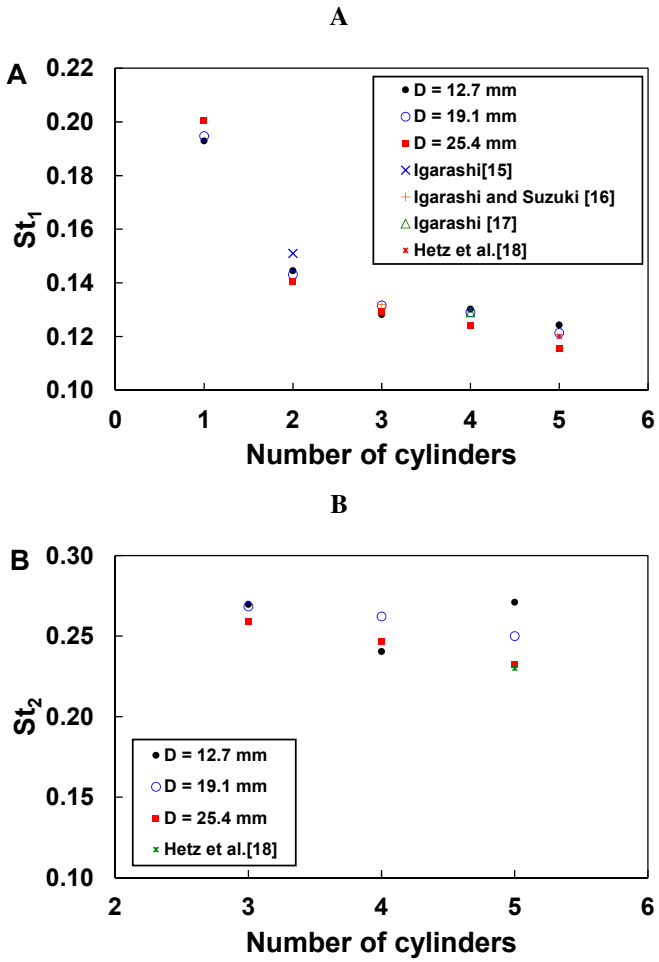


FIGURE 13. **A.** STROUHAL NUMBER St_1 OF COINCIDENCE RESONANCE AND **B.** STROUHAL NUMBER St_2 OF PRE-COINCIDENCE RESONANCE FOR ROWS OF DIFFERENT NUMBERS OF IN-LINE CYLINDERS

CONCLUSIONS

In this paper, the flow-excited acoustic resonance of an in-line row of cylinders is investigated. Cylinders of three different diameters of 12.7 mm, 19.1 mm, and 25.4 mm are tested in cross flow in an open-loop wind tunnel. Rows of different numbers of cylinders starting with a single cylinder up to five cylinders attached in-line with a fixed spacing ratio of $L/D = 2$ are tested in air velocities up to 160 m/s. Two different tube lengths in the span-wise direction, W = 127 mm and 76.2 mm, are used to test the effect of the cylinder's aspect ratio on acoustic resonance. For the small diameter of D = 12.7 mm, the attachment of more than one cylinder shows the same behaviour as a single cylinder except that the coincidence occurs at higher flow velocities. On the other hand, the attachment of more than one cylinder of higher diameter, D = 19.1 mm or 25.4 mm, at the

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same spacing ratio $L/D = 2$ causes the self-excitation of resonance at two discrete flow velocity regions that are wider than the case of a single cylinder. In addition, the increase in diameter significantly increases the normalized acoustic pressure of this pre-coincidence resonance. On the other hand, the change in the aspect ratio of the cylinder does not show significant effect on the acoustic response of in-line cylinders of the same diameter and spacing ratio.

The spectra of pressure oscillations for different numbers of cylinders show different characteristics. For a single cylinder, the vortex shedding at a Strouhal number of 0.2 is observed, and is responsible for the resonance at coincidence. For higher number of cylinders, similar periodic oscillations are responsible for the coincidence resonance at Strouhal numbers that decrease with the increasing number of cylinders. The Strouhal numbers of coincidence resonance is related to a periodic pattern where the flow oscillates downstream of the most downstream cylinder, and the row of cylinders behaves like a bluff-body. On the other hand, higher Strouhal numbers of around 0.25 are responsible for the pre-coincidence resonance, and are related to vortex shedding in the gap between successive cylinders.

The results of this study indicate that the pre-coincidence resonance detected in an in-line row of tubes may be overlooked when the cylinder diameter is small. As the pre-coincidence resonance shows characteristics similar to those of self-excited resonance in in-line tube bundle, the effect of diameter should be included in formulas predicting the occurrence of resonance and its acoustic pressure in tube bundles. Results obtained from bundles of tubes may result in dangerously misleading predictions when applied to bundles of different diameters.

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