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Characteristics of Acoustic Resonance Excitation by Flow Around Inline Cylinders

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Excitation of acoustic resonance by flow over tube bundles in heat exchangers can cause hazardous levels of acoustic pressure that may pose operational and environmental risks. The previous studies have indicated that inline arrangements of cylinders excite acoustic resonance of a nature different from that of a single cylinder. In this work, the excitation of acoustic resonance by cross-flow around inline arrangements of cylinders is experimentally investigated to identify the role of critical parameters on resonance characteristics. Results show that flow around inline tube bundles can excite acoustic resonance due to periodic flow oscillations over the cavity formed between successive cylinders rather than periodic wake phenomena. Based on precoincidence resonance characteristics, a criterion is introduced to predict the occurrence of acoustic resonance in inline arrangements of cylinders. The proposed parametric criterion does not only identify the potential for resonance excitation for inline arrangements of cylinders experimentally investigated in this work but it also provides a method to separate resonant from nonresonant cases for inline tube bundle data from the literature. [DOI: 10.1115/1.4044118]

1 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], control valves [2], cavities in flow ducts [3], and many other industrial applications [4]. 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 phenomenon of flow-excited acoustic resonance have been presented in the 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. In applications where tube arrays are subjected to cross flow, boundary layer separation and roll-up result in periodic vortex shedding. If the vortices are shed at a frequency that coincides with an acoustic cross-mode of the confining duct, the vorticity field acts as a sound source. The feedback provided by the acoustic particle velocity in the sound field enhances the vortex shedding. This completes a cycle that may lead to self-sustained acoustic resonance if the flow supplies the acoustic field with sufficient excitation energy to overcome the acoustic damping of the system. The acoustic modes that are able to exchange energy with the flow field are standing-wave modes in a direction normal to the tube axes and the flow direction [5].

The excitation of acoustic resonance due to the coupling between the acoustic mode and the flow field is a complex phenomenon with dependency on many geometric and dynamic variables. In order to gain more understanding of the details of flow-sound interactions and conditions that lead to the excitation of acoustic resonance, the researchers examined the aeroacoustic response of different simple arrangements of cylinders in cross flow, including both inline and staggered arrangements [6,7]. Blevins [8] reported that flow-excited acoustic resonance can be excited by vortex shedding from a single cylinder in cross-flow. Blevins and Bressler [1] reported that acoustic resonance may only be excited at flow velocities that correspond to coincidence of vortex shedding and acoustic mode frequencies, which become locked to the same frequency. They showed that the pressure amplitude depends on many acoustic and flow parameters including the inlet kinetic energy, Mach number, and cylinder diameter. Hanson et al. [9] experimentally investigated the self-excited aeroacoustic response of two side-by-side cylinders in cross-flow. They reported that bistable flow regimes in the absence of resonance are encountered for intermediate spacing ratios where two distinct vortex-shedding frequencies are observed. Interestingly, acoustic resonance occurs at a Strouhal number between those observed before the onset of resonance. They observed that the acoustic resonance synchronizes vortex shedding in the two wakes and thereby eliminates the bistable flow phenomenon. For larger spacing ratios, vortex shedding occurs at a single Strouhal number at which the acoustic resonance is excited. Arafa and Mohany [10] investigated side-by-side isolated cylinders and showed that acoustic resonance excitation takes place as a result of the complex interaction between different sources of acoustic resonance. Ziada and Oengören [6,11] found that flow-excited acoustic resonance can be excited by cross-flow over closely backed inline arrays of cylinders. The characteristics of the excited resonance suggested that the instability of the jet in the tube lanes is the main source of resonance excitation. Mohany [12] investigated the excitation of acoustic resonance by flow around two tandem cylinders of the same diameter in cross-flow. 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 resonant noise. More notably, resonance is also observed at much lower flow velocities than necessary for a coincidence between the free-field vortex shedding frequency and the acoustic cross-mode frequency. This earlier resonance is referred to as the *precoincidence resonance*. Mohany and Ziada [13] investigated the effect of diameter and spacing on the excitation of precoincidence resonance by the flow around two tandem cylinders by investigating a range of spacing ratios ranging from 1.5 to 2.5 to cover the proximity interference region for cylinders of diameters between 7.6 mm and 27.5 mm. Results showed that in comparison with resonance excitation by flow around a single cylinder, precoincidence 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 inline tube bundles. They proposed

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that the precoincidence resonance is the main contributor to resonance in the case of inline tube bundles. Mohany and Ziada [13] reported that precoincidence resonance did not occur systemically at various cases of different diameters. When the spacing ratio between the cylinders increased, the minimum diameter required to excite the precoincidence resonance was higher, indicating a major effect of the diameter on the excitation of acoustic resonance. Precoincidence resonance was less likely to occur for smaller cylinder diameters. Mohany and Ziada [14] attributed the excitation of precoincidence resonance to the instability of the shear layer in the gap between the two cylinders. On the contrary, the acoustic source for the coincidence resonance is vortex shedding in the wake of the downstream cylinder. A numerical simulation of the coincidence and precoincidence acoustic resonance was carried out to identify the acoustic sources around the cylinders [15]. For the precoincidence resonance, the acoustic source is located in the gap between the cylinders. Mohany and Ziada [13] noted that the diameter of the cylinders has a significant effect on the nature and lock-in region of precoincidence resonance and should be taken into account to predict the excitation of acoustic resonance. More recently, Shaaban and Mohany [16,17] investigated the flow field and the acoustic excitation around three inline cylinders and reported that the flow around the arrangement of three unevenly spaced inline cylinders may excite precoincidence acoustic resonance under a set of conditions relating to the uneven spacing, the flow velocity, and the cylinder diameter. However, no attempt has been made to identify a criterion to be used to predict if acoustic resonance is expected to occur.

Despite the relative abundance of such arrangements in engineering applications, little information is available in the literature on the flow around an inline arrangement of more than two cylinders. Although the flow around an inline arrangement of cylinders exhibits many periodic features that are different depending on the number of cylinders [18–20], the available studies of more than two cylinders arranged inline are confined to the description of the flow patterns around the row at a small range of Reynolds number, featuring a limited vision of the periodic behavior. Moreover, acoustic resonance excitation by flow around a row of more than two inline cylinders has never been investigated. Building upon the knowledge revealed by investigating the arrangement of two tandem cylinders, the arrangement of several inline cylinders resembles a gradual step of complexity toward modeling acoustic resonance excitation in inline tube bundles. The effect of the vast differences in flow patterns and bistable phenomena on the aeroacoustic response has not been investigated, and it is not known if excitation of acoustic resonance around such arrangements is possible. During acoustic resonance, the flow oscillation is two-dimensional as the resonant sound field synchronizes the vortex shedding along the cylinder span [8]. In addition, significant effect of the cylinder span-to-diameter ratio on the flow-excited acoustic resonance has been reported for some arrangements such as single bare and finned cylinders [8,21,22]. However, it is unclear if cylinder spanwise length can impact the coherence between cylinders, thus playing a role in acoustic resonance excitation for arrangements of inline cylinders. The range of cylinder spanwise length varies widely in practice, while experimental data are often reported for a single or a limited range of spanwise length. This results in the dismissal of the spanwise length in formulation of the criteria of acoustic resonance excitation. The understanding of the role of different flow and acoustic parameters on the excitation mechanism of precoincidence resonance is necessary to identify the parameters that control the flow–sound interactions and result in acoustic resonance. Therefore, this work experimentally investigates the excitation of acoustic resonance by the flow around arrangements of inline cylinders in cross flow and proposes a criterion to predict the acoustic resonance excitation.

2 Experimental Setup

A schematic drawing of the experimental setup is shown in Fig. 1. The experiments were performed in an open loop wind tunnel. 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 Fig. 1, has a resonance frequency of 670 Hz. The inlet section of the apparatus is connected 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. Wind tunnels of different width were used to allow testing cylinders of different spanwise length. The configuration of the test section is able to cause self-excited resonance at the frequency of the first acoustic mode.

To test the acoustic resonance occurrence and characteristics, cylinders are attached in inline configurations in cross-flow. A single cylinder, and an inline 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 centers of the cylinders are separated by $L = 2.00\ D$. Three different diameters are separately tested, namely 12.7 mm, 19.1 mm, and 25.4 mm. Each diameter is tested in three different test sections of three different spanwise widths of $B = 76$ mm, 127 mm, and 178 mm, which yield a range of aspect ratios between $B/D = 3$ and 14.

The acoustic pressure of the acoustic standing wave is measured at the acoustic pressure antinode. This is done using a 0.25 in. prepolarized pressure-field microphones model 377A12a, with a sensitivity of 0.25 mV/Pa and can work up to a maximum amplitude of 187 dB. The microphones are attached to a pre-amplifier model 426B03. The combined open circuit sensitivity referenced to 1 V/Pa is −72 dB (±3 dB). Three microphones are flush mounted at the top wall of the test section at the antinode of the acoustic pressure at a spacing of 1 in, with the middle microphone attached exactly opposite to the middle of the cylinder configuration. The pressure values are recorded with a sampling rate of 11.025 kHz for 30 s. The acoustic pressure measurements are transformed into the frequency domain by taking an average of 30 ensembles to analyze 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 upstream flow velocity is then extracted. For each different configuration of cylinders, the maximum acoustic pressure measured by the three microphones is selected as the antinodal acoustic pressure.

The acoustic mode of the test section with the cylinders installed was calculated by numerically solving the homogeneous Helmholtz equation. For the two-dimensional modes of an x–y plane with uniform wall impedance, acoustic pressure at any position $P(x, y, z)$ satisfies

$$-\nabla^2 p - k^2 p = 0 \tag{1}$$

The acoustic pressure on each wall of impedance Z_j at a wave number k needs to satisfy

$$-\nabla p \cdot \boldsymbol{n} = -i\frac{\rho c_0}{Z_j} kp \tag{2}$$

Infinite acoustic impedance boundary condition was assigned to solid walls at $y/D = \pm 5$, as well as walls of cylinders at $(x - x_c)^2 + (y - y_c)^2 = D^2/4$, where (x_c, y_c) are locations of cylinder centers. The boundary conditions at the opposite open ends at $x/D = \pm 12$ were specified as flanged open ends. The eigenvalues of this problem were calculated using a two-dimensional finite element analysis. For the case of three inline cylinders at a spacing ratio of $L/D = 2.00$, the acoustic pressure amplitude of the first transverse mode of the test section is shown in Fig. 2. The maximum acoustic pressure amplitude occurs on the boundaries of the test section at two opposite locations that are 180 deg out of phase

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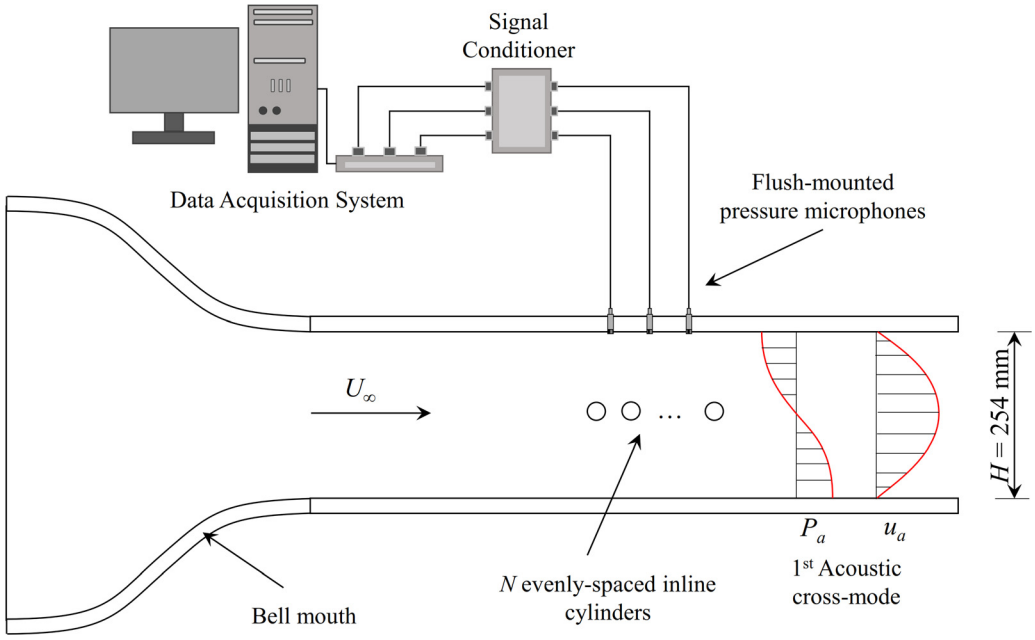


Fig. 1 A schematic of the experimental setup

with each other, exactly opposite to the middle point of the cylinder arrangement. The calculated acoustic cross-mode frequency was always lower than the cutoff frequency of the duct $f = c/2H$, which indicates that the acoustic mode becomes trapped in the duct, resulting in severe amplitudes of oscillations.

3 Aeroacoustic Response of a Row of Inline Cylinders

To characterize the acoustic response of each cylinder arrangement, the normalized acoustic pressure P^* is calculated at every value of the normalized flow velocity U_r, where

$$P^* = \frac{P}{0.5\rho U_\infty^2 M} \quad \text{and} \quad U_r = \frac{U_\infty}{f_a D} \tag{3}$$

where P is the root-mean-square acoustic pressure, U_∞ is the free-stream flow velocity, ρ is the fluid density, f_a is the frequency of the first acoustic cross-mode of the duct, D is the cylinder diameter, and M is the flow Mach number. This normalized form is used to scale the flow-excited acoustic resonance according to the theory of aeroacoustic sound [23]. The frequency of periodic phenomena, f, is shown in the form of Strouhal number St, defined as

$$\text{St} = \frac{fD}{U_\infty} \tag{4}$$

The contour plots in Fig. 3 show the effect of flow velocity on the spectral characteristics of the recorded acoustic pressure signal at

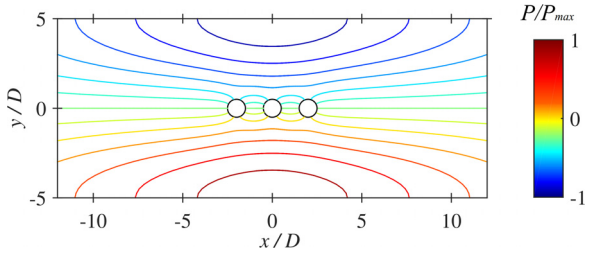


Fig. 2 Contours of normalized acoustic pressure amplitude for the first acoustic transverse mode around three inline cylinders at $L/D = 2.00$

the pressure antinode of the first acoustic mode. The yellow dashed line is superimposed on the peaks of gradually increasing frequency as the flow velocity increases. In Fig. 3, the cases with two to five inline cylinders illustrate the effects of the cylinder diameter on the aeroacoustic response for an increasing number of cylinders. The acoustic mode frequency is identified as a vertical line. At coincidence of the gradually increasing frequency of vortex shedding and the acoustic cross-mode frequency, coincidence resonance takes place for all cases, characterized with severe levels of acoustic pressure that result in acoustic particle velocities of up to 10% of the mean flow velocity. Whereas another episode of resonance takes place at lower flow velocity for some cases. The acoustic resonance occurrence at lower flow velocity is similar to precoincidence resonance reported by Mohany [12] for the case of two tandem cylinders in terms of the range of flow velocities.

For all cases, the increase in the number of cylinders results in a decrease in the Strouhal number of coincidence resonance excitation as the row of cylinders approaches the case of a slender object. While the identified Strouhal number is related to the resonance at coincidence with the acoustic mode frequency, the precoincidence resonance occurs suddenly with no apparent exciting peaks for most cases. An interesting behavior is observed for the case with $D = 25.4$ mm and five inline cylinders. For that case, another gradually increasing peak series can be seen in the spectra of acoustic pressure, which ultimately coincides with the acoustic mode earlier than the coincidence resonance. The higher Strouhal number associated with this peak seems to be consistent with the excitation of precoincidence resonance for all cases. A particularly important observation is that the higher Strouhal number is nearly double the coincidence Strouhal number. The same higher Strouhal number appears, although weakly, in cases with this particular number of cylinders. This can be due to the interaction between the periodic flow phenomena in the gaps between cylinders and the wake of the cylinder arrangement. Due to the fact that the gaps are identical in each arrangement, the sound sources during precoincidence resonance excitation are expected to be similar in terms of frequency during excitation of acoustic resonance. The phasing and the relative strength of such sources would depend on the interactions that take place between gaps depending on the spacing ratio and the flow structure at subsequent gaps. In this case, the excitation sources are of the same

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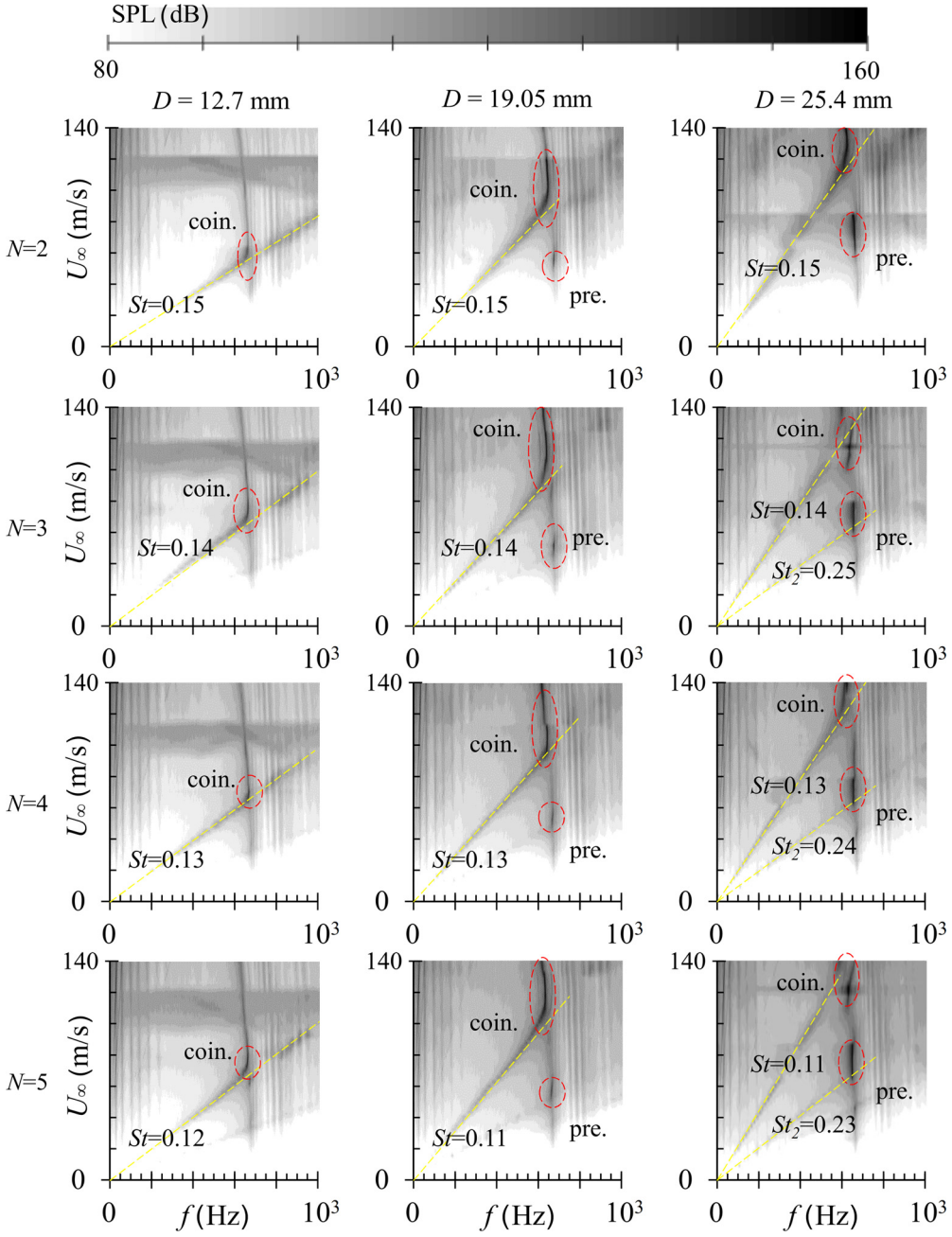


Fig. 3 Effect of the number of cylinders on the spectral characteristics of the aeroacoustic response of an inline row of cylinders with a spanwise length of $B = 76$ mm and a spacing ratio $L/D = 2.00$ for all cases

frequency, which explains the fundamentally similar aeroacoustic response during excitation of precoincidence resonance by flow around arrangements of inline cylinders of the same diameter, regardless of the number of cylinders.

While the increase in the number of cylinders has a gradual effect on the aeroacoustic response, the effect of the cylinder diameter is major and more pronounced. The precoincidence resonance is not excited for cases with a diameter of $D = 12.7$ mm and any number of inline cylinders. The increase of the diameter to $D = 19.05$ mm or $D = 25.4$ mm results in the excitation of precoincidence resonance. This excitation is only a result of the increase in the diameter as the spacing ratio L/D was kept constant at 2.00 for all configurations. The requirement for a minimum diameter for excitation of precoincidence resonance at velocities lower than necessary for frequency coincidence proves that the diameter is an important factor that has to be included in the evaluation of the susceptibility of inline arrangements of cylinders to acoustic resonance excitation. The increase in diameter has several consequences that have effects on the interactions responsible for precoincidence resonance excitation. First, the increase in the cylinder diameter increases spacing beyond a minimum limit required for self-sustainable periodic perturbations to form between cylinders [24]. This explains why tighter inline arrays with smaller L/D are less susceptible for excitation as there is lower spacing between cylinders, which can provide predictions when the diameter is limited to a very small range. However, using the factor L/D can cause false predictions as the diameter gets smaller so that the spacing between cylinders becomes not sufficient for periodic perturbations to exist. Second, increasing cylinder diameter also requires a higher flow velocity to excite resonance for the same acoustic mode wavelength and the same spacing ratio. Increasing the diameter to wavelength ratio,

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equivalent to D/H, therefore, increases the available flow energy at resonance, which results in a significant increase in the predicted acoustic pressure at resonance. Moreover, increasing the space occupied by the mass of the cylinder within the acoustic domain increases the added mass which decreases the acoustic mode frequency further below the cutoff frequency $c/2H$ required for acoustic propagation out of the acoustic domain. This results in less acoustic radiation and higher localized acoustic pressure amplitudes around the acoustic source [17].

As shown in Fig. 4, the increase in the acoustic pressure due to the increase in the number of inline cylinders, and therefore, sound sources in the gaps, is not linear. For precoincidence resonance, the sound pressure level at the peak of resonance depends significantly on the cylinder diameter, but has no significant dependence on the number of cylinders in the row. This behavior suggests that adding more cylinders can cause aerodynamic interaction between sound sources that lead to a diminishing contribution of each added sound source, as observed by Shaaban and Ziada [25] for tandem cavities. The number of cylinders showed similar effect on the excitation of coincidence resonance, where the sound pressure level was not significantly changed when more than three inline cylinders were used.

Figure 5 shows the normalized acoustic pressure P^* over a range of reduced flow velocity for four different cases featuring a different number of inline cylinders. In each plot, results for three different cylinder diameters are presented. Results show that as the reduced velocity is increased, high values of normalized acoustic pressure can potentially arise at two different ranges of reduced velocities. The earlier precoincidence resonance is observed at reduced velocities of $U_r = 3.5$–5.0. The excitation of precoincidence resonance in this range is determined by the diameter of the cylinders. For the smallest cylinder diameter of $D = 12.7$ mm, precoincidence resonance was not excited by flow around any number of inline cylinders. Moreover, the normalized acoustic pressure of precoincidence resonance increases from around $P^* = 1.0$ for $D = 19.1$ mm to much higher values for $D = 25.4$ mm. The characteristics of this range of resonance in terms of the range of reduced velocities and the normalized acoustic pressure were not significantly affected by the number of cylinders in the arrangement.

As reduced velocity is increased beyond the precoincidence excitation range, the acoustic pressure decreases to the level of background noise. Figure 5 shows that the coincidence resonance is excited at higher values of reduced flow velocity. Unlike precoincidence, the number of cylinders has an effect on the range of reduced velocity at which coincidence resonance is excited. Although coincidence resonance results in extreme levels of acoustic pressure, equivalent to acoustic particle velocities in the order of a tenth of the mean flow velocity, the normalized acoustic pressure is lower than that of the precoincidence resonance for the highest diameter $D = 25.4$ mm. This is due to the higher flow energy available at the range of coincidence resonance. It is important to note that while the number of cylinders carried little weight in determining the resonance sound pressure level, the number of cylinders had some effect on the lock-in range of the precoincidence resonance.

The spectra of the sound pressure level for an inline row of five cylinders with cylinder spanwise length of $B = 76$ mm and 178 mm, equivalent to a range of aspect ratios between $B/D = 3$ and 14, respectively, are shown in Fig. 6. The spectral characteristics of the acoustic pressure signal show no significant effect of the cylinder spanwise length on the excitation of resonance in terms of the range of flow velocities or the Strouhal number. Notably, the frequency spectra of an inline row of five cylinders of the smallest diameter $D = 12.7$ mm show a series of peaks at a lower flow velocity and a higher frequency. This series of peaks is similar to the periodic peaks responsible for the excitation of precoincidence resonance. The inability of these peaks to excite significant acoustic resonance is related to the smaller gap between each two successive cylinders, which does not reach a length sufficient for self-sustained shear layer oscillations to couple with the acoustic mode and result in acoustic resonance.

Figure 7 shows the effect of cylinder diameter and number of inline cylinders on the Strouhal number at the peak of acoustic resonance excitation. Results showed that cylinder diameter has no significant effect on the Strouhal number, although the Strouhal number for cylinders of the smallest diameter is slightly higher for the cases with fewer cylinders. This is due to the fact that resonance is excited at highly turbulent conditions where Reynolds number has little effect on the Strouhal number. Cylinder diameter has a more pronounced effect on the Strouhal number especially for coincidence resonance. This suggests that the increase in the number of cylinders increases the effective diameter of the row, causing vortex shedding that approaches that of a slender object oriented in the streamwise direction. The values of Strouhal number for precoincidence resonance excitation are indicative of self-sustained periodic oscillations over the gap between the two cylinders. In such case, the characteristics length of such oscillations would be in the order of the center-to-center spacing between each two successive cylinders. This confirms that a minimum gap spacing is required for excitation of this region of resonance. It also suggests that coexisting acoustic sources might interact in a way that would be dependent on the center-to-center spacing and the cylinder diameter. Despite having little effect on the amplitude of acoustic resonance, the number of cylinders plays an important role in determining the susceptibility of the configuration to excitation of acoustic resonance due to its influence on the Strouhal number and its effect on the available flow energy and the flow pattern around the cylinder arrangement.

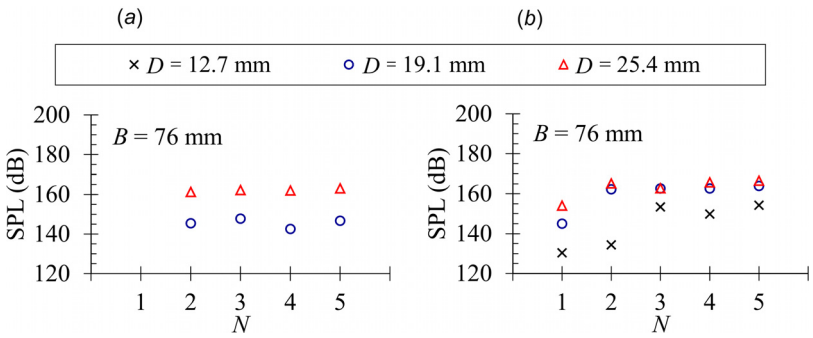


Fig. 4 Effect of the number of cylinders on the sound pressure level of precoincidence and coincidence resonance for inline cylinder arrangements of different diameters: (*a*) pre-coincidence and (*b*) coincidence

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4 Prediction of Acoustic Resonance Excitation in Inline Cylinder Arrays

The excitation of acoustic resonance can pose a hazard to the operation of industrial components that rely on tube arrays. Several criteria have been based upon collected data in different experimental conditions to predict the excitation of acoustic resonance by flow around different arrangements of tubes in cross flow. However, the incomplete understanding of the exciting phenomena in the tube bundle often results in unreliable predictions. Chen and Young [26] used values of spacing ratio, Reynolds number, and Strouhal number to predict resonance excitation. However, the verification of the validity of this criterion showed that the resonance may be overlooked in industrial conditions, as the criterion does not allow geometric or gas properties scaling. Fitzpatrick [27] modified that criterion to account for geometric scaling. Blevins and Bressler [28] presented maps of the resonance occurrence in the transverse-longitudinal plane for both inline and staggered tube bundles by plotting data obtained from several studies based on the streamwise and transverse spacing ratios. Ziada et al. [5] noted that the charts only give a general qualitative description of the fact that closely packed cylinder arrays are not susceptible to excitation. However, experimental evidence shows significant deviation from the limits specified for resonance in the charts [2,29]. Furthermore, the charts do not take the resonance frequency or flow velocity into consideration, which are directly related to the energy available to excite the resonance. Many criteria proposed to predict the self-excitation of noise in tube bundles were reviewed by Fitzpatrick [27] who noted that the available criteria are generally empirical and often result in contradicting predictions. Ziada et al. [30] noted that the available criteria do not allow for geometric scaling by implying that acoustic resonance excitation depends mainly on the spacing to diameter ratio of the bundle. Weaver et al. [31] suggested that the frequency of the source exciting the acoustic resonance depends on the spacing ratio of the cylinders for several different arrangements of tube bundles. Eisinger et al. [32] proposed that the acoustic resonance excitation is dependent on the available flow excitation energy. However, the acoustic damping of the system was not taken into account. The minimum energy required for the excitation of acoustic resonance was deduced from a large number of experiments. In addition, the input excitation energy is a function of the cylinder diameter to width ratio. However, the parameters used by Eisinger et al. [32] imply that the value of cylinder diameter does not explicitly affect the occurrence of the acoustic resonance.

The excitation of resonance by flow around an inline arrangement of cylinder offers a valuable simplification to the problem of resonance excitation by the flow inside an inline tube bundle. As can be seen in Fig. 8, clear similarities can be seen between the aeroacoustic response of an inline tube bundle and the case of an

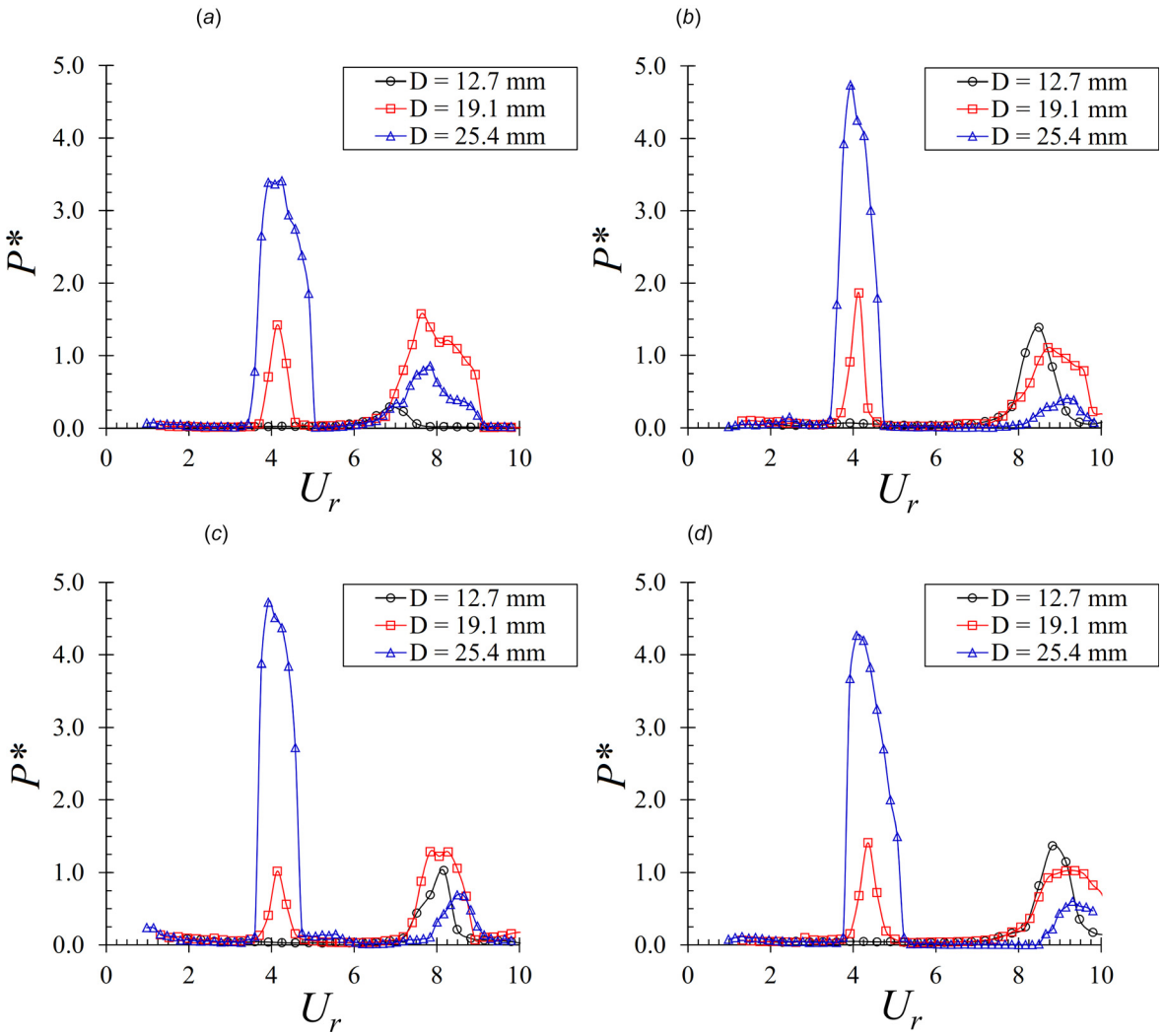


Fig. 5 Effect of number of cylinders and cylinder diameter on the acoustic response of inline arrangements of cylinders of spanwise length $B = 76$ mm at a spacing ratio $L/D = 2.0$ (*a*) two inline cylinders, (*b*) three inline cylinders, (*c*) four inline cylinders, and (*d*) five inline cylinders

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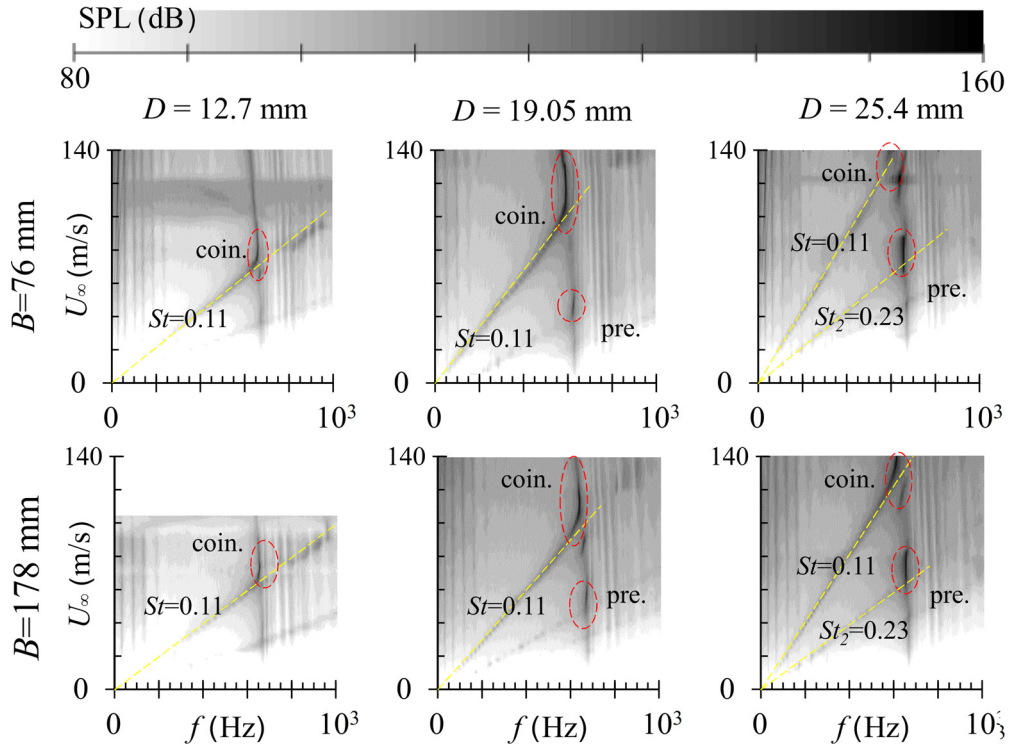


Fig. 6 Spectral characteristics of the aeroacoustic response of five inline cylinders of different spanwise lengths

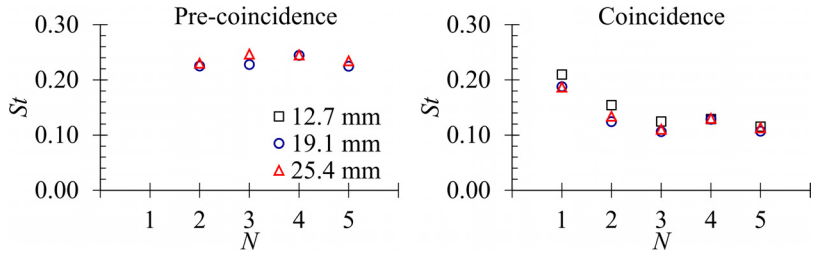


Fig. 7 Strouhal number of acoustic resonance excitation for inline arrangements of cylinders

inline arrangement of cylinders. The sound pressure level of the cases of two and five inline cylinders at a spacing ratio of 2.00 is compared to the sound pressure level for an inline tube bundle of an inline spacing ratio of 2.1 and a transverse spacing ratio of 2.5. As the number of cylinders is increased from two to five, the reduced velocity at which acoustic resonance is excited and the sound pressure level increases abruptly approaches the value observed for the inline tube bundle. Although flow around a single cylinder is expected to excite resonance at a reduced velocity around 5.0, the range of reduced velocities at which such resonance would prevail is much smaller than the case of five inline cylinders. The behavior shown in Fig. 8 suggests that the excitation of the earlier resonance in the case of an inline arrangement of cylinders is similar in nature to the excitation of acoustic resonance in inline tube bundles. As revealed from the previous discussion, precoincidence resonance excitation is expected to occur at lower flow velocities, and therefore, is more relevant to the discussion of acoustic resonance excitation in inline tube bundles. The major role identified for the diameter in determining whether resonance excitation takes place has to be taken into account in predicting the excitation of acoustic resonance in tube bundles. Moreover, the experimental observations show that the spanwise length of the cylinder does not play a significant role during excitation of acoustic resonance. This is a result of the two-dimensional nature of the flow field which is a result of the coupling with a fundamentally two-dimensional acoustic mode [1,15].

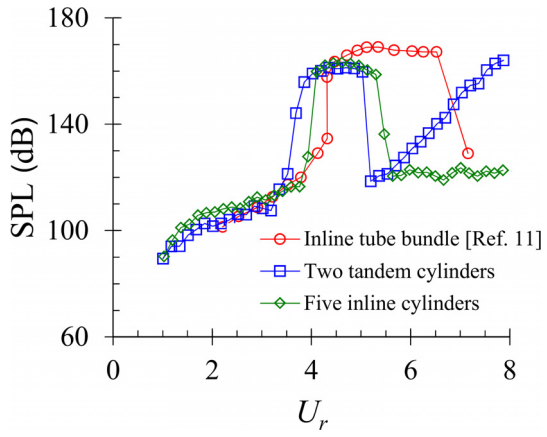


Fig. 8 Sound pressure level in the cases of two and five cylinders of $D = 25.4$ mm and $L/D = 2.0$, compared with that of an inline tube bundle with $L/D = 2.1$ [11]

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The current available formula for the prediction of acoustic resonance does not fully account for the observations stated above. For instance, Chen and Young [26] acknowledge the effect of the diameter by including Re in their resonance excitation parameter $\Psi = \mathrm{Re}/\mathrm{St} * \alpha$, where α is a function of inline and transverse spacing ratios. However, the ratio Re/St is in the order of magnitude of U^2, which only captures the effect of diameter on the input kinetic energy, and does not account for its effect on the minimum length required for acoustic sources to exist in the gaps or on the reduction in the acoustic radiation. The effect of the number of cylinders on the Strouhal number was not included in favor of explicitly including the Strouhal number, requiring an estimation of the Strouhal number of the periodic excitation sources in each application. As a result, the threshold initially identified by Chen and Young [26] was subsequently adjusted for application on actual units [27], possibly because of different cylinder diameter and number of cylinders.

Modifications by Fitzpatrick [27] to the resonance prediction parameter included the use of $\sqrt{\mathrm{Re}/M}/\mathrm{St} * \beta$, where β is a function of inline spacing ratio. The parameter takes into effect the ratio $\sqrt{U/D}$. According to Fitzpatrick [27], excitation of resonance is expected if the parameter falls within limits that depend on the inline spacing ratio, which shows that resonance might not be expected for cases with smaller diameters. However, the effect of the number of cylinders was not taken into account in this method which resulted in unreliable predictions due to the lack of data at the upper boundary as noted by Ziada et al. [30]. Fitzpatrick [27] also noted that extreme predictions of this method are due to physical size of the tubes, which suggests that cylinder diameter is not fully accounted for. For similar reasons, the other available methods do not provide reliable predictions of the excitation of resonance by inline tube bundles due to the dismissal of significant parameters in favor of the spacing ratio to allow for scaling. This highlights the need for the inclusion of a different set of parameters, including the explicit use of the cylinder diameter D and the number of cylinders N, depending on observations done on the precoincidence resonance which is excited by acoustic sources of the same nature.

To remedy the shortcomings of the previous criteria, Ziada et al. [30] formulated a resonance parameter taking into consideration the acoustical Reynolds number, based upon the sound speed c, and the critical flow Reynolds number Re based on the critical velocity that coincides with a transverse acoustic mode. This approach takes into consideration the effect of diameter on the acoustic radiation, but does not account for the source of the aeroacoustic resonance excitation due to the inclusion of a small range of geometric and flow conditions. Therefore, there is a need to account for the fact that resonance excitation in inline tube bundles is excited by sound sources in the gaps between cylinders that are similar to precoincidence resonance rather than sound sources created by coupling between acoustic modes and wake shedding.

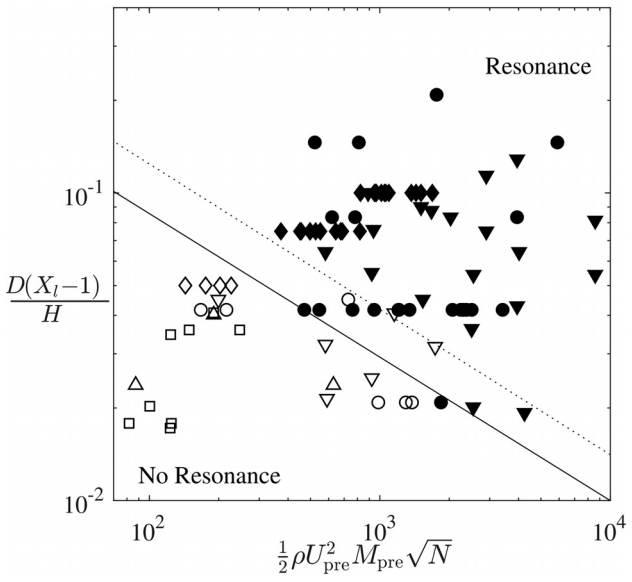


Fig. 9 Parametric criterion for acoustic resonance excitation based on parameters affecting precoincidence resonance in inline arrangements of cylinders. △, Ziada et al. [30]; ○, ● Blevins and Bressler [1]; □, Eisinger et al. [32]; ▽,▼ Mohany [33]; and ◇,◆ Present work. Solid symbols are resonant cases and void symbols are nonresonant cases.

Figure 9 shows the data points of inline configurations of cylinders plotted taking into effect the main parameters that influence the excitation of precoincidence acoustic resonance. On the vertical axis, the parameter $D(X_l - 1)/H$ includes the effect of the arrangement geometry, including the diameter D and the center-to-center spacing ratio $X_l = L/D$, normalized by the test section height H, which is proportional to the wavelength of the first acoustic cross-mode. The horizontal axis includes the effect of the number of cylinders, the flow dynamic head, and the Mach number at the conditions for precoincidence resonance. To evaluate these parameters, the Strouhal number of precoincidence resonance should be obtained according to the geometry of the configuration. To test a particular design of an inline tube bundle against the risk of precoincidence resonance excitation, the value of U_{pre} is evaluated at the coincidence of the gap shedding frequency and the acoustic mode frequency. The Strouhal number can be used to calculate the flow velocity U_{pre} at which the periodic instability characterized by the Strouhal number acts at the same frequency as the first acoustic cross-mode of the duct, such as

$$U_{\mathrm{pre}} = \frac{f_a D}{St} \tag{5}$$

In the case of an inline arrangement of cylinders, the Strouhal number is close to 0.24, as shown in Fig. 4. The value of f_a is the lowest acoustic cross-mode frequency of the duct, which can be theoretically estimated using numerical methods [15]. The values of Mach number and the dynamic head of the flow velocity are calculated at this flow velocity. There is a risk of acoustic resonance excitation if the flow velocity U_{pre} falls within operation range and the design falls above the solid line in Fig. 9. It can be seen that as the flow has higher Mach number and Reynolds number, instabilities are more likely to excite precoincidence resonance. Moreover, arrangements with higher diameters and spacing ratios relative to the wavelength are more susceptible to excitation of acoustic resonance. Arrangements with more cylinders are more susceptible to excitation of acoustic resonance, although the contribution of the number of cylinders to the acoustic resonance excitation diminishes as the number of cylinders in the arrangement increases. The experimental observations resulted in a data fit using the parameter $\sqrt{N}$. For a nonresonant design, the parameter $D(X_l - 1)/H$ should not exceed the lower safe boundary line at the corresponding flow parameters. As flow has more energy available, tighter designs are needed to ensure that flow-excited acoustic resonance does not materialize, which agrees with the experimental observations.

5 Conclusion

In this work, the excitation of acoustic resonance by fluid flow around inline cylinder arrangements is investigated to identify the influence of critical parameters on the excitation and characteristics of acoustic resonance. Inline arrangements of two to five cylinders were investigated due to their similar aeroacoustic response to the case of an inline tube bundle of the same spacing ratio. Cylinders of different diameters were subjected to cross flow of air at velocities of up to 140 m/s. High velocity flow around all tested arrangements of inline cylinders was able to excite acoustic

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resonance at the coincidence of the acoustic mode frequency and the free-field vortex shedding frequency. On the other hand, pre-coincidence resonance was only excited at lower flow velocities around inline arrangements of cylinders of higher diameters. The source of excitation of precoincidence resonance is created as the flow over the cavity formed in the gap between the two cylinders becomes unstable. The number of cylinders has a significant effect on the Strouhal number at which coincidence resonance is excited. More importantly, the sound pressure level and range of flow velocity of precoincidence resonance excitation approach those of an inline tube bundle as the number of inline cylinder increases. Arrangements of cylinders of higher diameter are more likely to excite acoustic resonance and result in higher normalized acoustic pressure at precoincidence resonance. A criterion is proposed to predict the excitation of precoincidence acoustic resonance using two parametric variables. The application of the criterion on inline tube bundles successfully separates resonant from nonresonant cases.

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