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EXCITATION OF ACOUSTIC RESONANCE BY CROSS FLUID FLOW OVER THREE INLINE CYLINDERS

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ABSTRACT

The excitation of acoustic resonance by cross fluid flow over cylinders of various arrangements has been frequently reported in a vast spectrum of applications. The resulting severe noise levels and the associated structural vibration can cause significant damage to critical components and often raises environmental concerns. When three cylinders in cross flow are in proximity of each other, recent studies reported the occurrence of resonance due to more than one excitation mechanism. Resonance is excited by the oscillating wake structures as well as from the interference of flow structures in the gaps between successive cylinders. In this work, simultaneous measurements of the instantaneous lift force affecting three rigidly-fixed cylinders arranged in a row and subject to cross-flow are performed at resonant and non-resonant conditions. The magnitudes of dynamic lift forces on successive cylinders are analyzed to identify the contribution of the individual cylinders as well as the contribution of the interactions between the successive cylinders on the flow-excited acoustic resonance.

INTRODUCTION

The occurrence of flow-excited acoustic resonance in nuclear power plants and other critical applications can pose significant economic and environmental hazard [1]. The extreme levels of noise caused by flow-excited acoustic resonance typically result from unintended coupling between oscillating flow regimes and the acoustic field. Arrangements of cylinders in cross flow shed vortices at a frequency that depends on the flow velocity, cylinder diameter, and the arrangement of cylinders[2], so that

$$St = \frac{fD}{U}$$

where St is the Strouhal number, f is the vortex shedding frequency, D is the cylinder diameter, and U is the free stream velocity. The reduced flow velocity U_r at which resonance is expected to occur is dependent on the cylinder diameter and the value of acoustic mode frequency f_a, where

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

For a single cylinder at high Reynolds numbers, *St* is 0.20 , while it depends on the number and spacing of cylinders for an inline row of cylinders. Therefore, increasing cross-flow velocity causes vortex shedding frequency to increase, and to eventually coincide with the acoustic cross mode frequency of the duct. If the acoustic cross mode is not sufficiently damped, flow energy can supply the acoustic mode with energy, causing severe resonance[3].

Mohany and Ziada [4] reported that for the arrangement of two tandem cylinders in proximity, resonance occurs at two distinctive stages. An early resonance occurs prior to frequency coincidence between vortex shedding and the acoustic cross mode, and is related to fluctuating flow regimes in the gap between the cylinders. Resonance also occurs at the coincidence between wake vortex shedding and the first acoustic cross mode. The occurence of the earlier pre-coincidence resonance depends on the diameter as well as the spacing between the two cylinders. Shaaban and Mohany [2] observed that pre-coincidence resonance can occur for the configuration of a row of several inline cylinders.

To identify the effect of acoustic resonance on the dynamic lift acting on the arrangements of a single and two-tandem cylinders in cross flow, Mohany and Ziada [5, 6] performed direct lift measurements in presence and absence of acoustic resonance. They showed that a dipole sound source is an accurate representation of the coupling mechanism during acoustic resonance. Moreover, their results assert that the dipole source is related to the dynamic lift force on the cylinders. During resonance, Mohany and Ziada [5] observed a significant increase in the dynamic lift forces on the cylinders. Their study however does not show simultaneous measurements of the force on the two cylinders, nor do they include other cylinder arrangements. Flow around three inline cylinders can be significantly different than that of two tandem cylinders[7], which can affect energy exchange mechanism during acoustic resonance. In addition, reports of the occurrence of pre-coincidence resonance for an inline row of cylinder do not provide enough insight about the location of the sound source, which is needed in order to understand and counteract the occurrence of this resonance in such configurations. Therefore, this study addresses the effect of pre-coincidence and coincidence acoustic resonance conditions on the dynamic lift force on three inline cylinders.

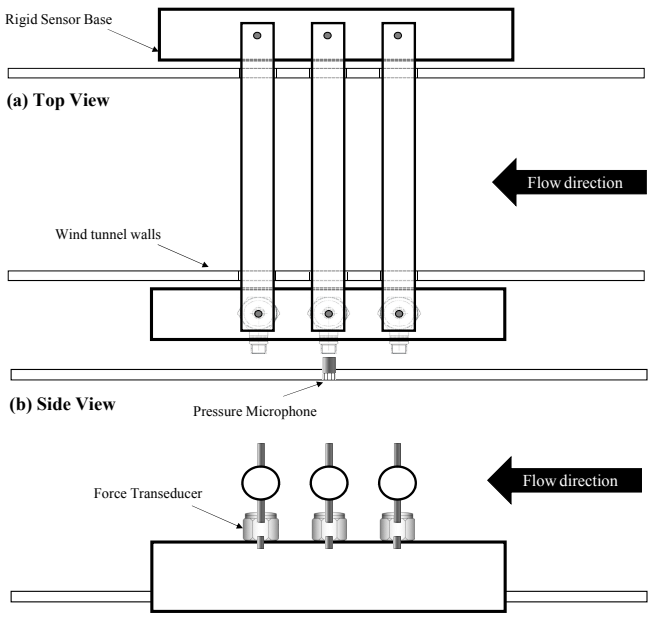


FIGURE 1. SCHEMATIC OF THE EXPERIMENTAL SETUP

EXPERIMENTAL APPARATUS

The aeroacoustic response and lift force measurements on three inline cylinders are carried out in an open wind tunnel. The facility blower driven by a controlled variable frequency motor allows for air velocities up to 150 m/s. Air enters the wind tunnel through a parabolic bell mouth section to minimize turbulence. Figure 1 shows top and side views of the experimental setup. The three cylinders are located within the rectangular wind tunnel section of width 127 mm parallel to the cylinder axis. The diameter of the cylinders is 1.0 inch, and the center to center spacing between the cylinders is 2.0, so that the cylinders are in proximity interference. The wind tunnel height, perpendicular to the axis of the cylinders is fixed at 254 mm over its length, and the first acoustic cross mode frequency is f = 660 Hz. The three cylinders pass through the wind tunnel walls with a gap of 1.5 mm to isolate the cylinders from any vibration in the wind tunnel body. Acoustic pressure is measured at the top wall exactly above the middle cylinder axis, using a 1/4" pressure PCB 378A12 microphone. Lift force is measured using three PCB 208C01 force transducers. Cylinders are mounted using standard threads that are connected directly into the body of the force sensors. The force sensors are mounted rigidly on a steel base using fine threads.

At each velocity, data of acoustic pressure and dy-

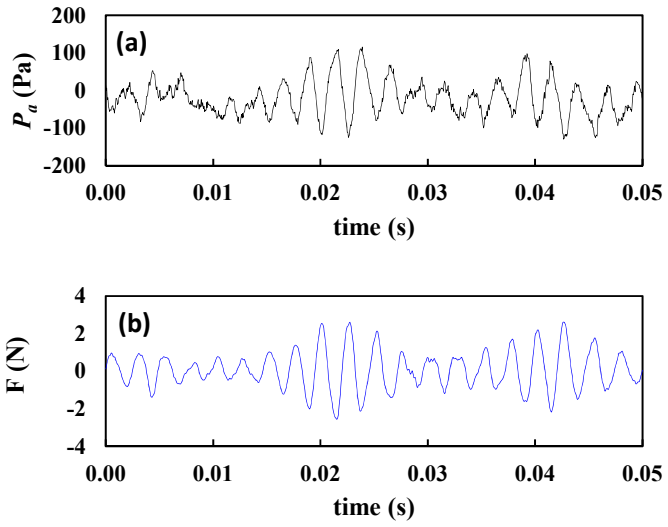


FIGURE 2. MEASURED SIGNALS FROM THE (a) MICROPHONE AND (b) FORCE SENSOR FOR A SINGLE CYLINDER AT U = 49 M/S.

namic lift force is recorded at a sampling rate of 40 kHz for 60 seconds. To extract the dominant frequency, spectra of the signals are calculated using 60 ensembles into an average FFT with a resolution of 1 Hz. The force is calculated as the root mean square fluctuations of the lift component.

RESULTS AND DISCUSSION

Figure 2 shows a typical signal measured by the microphone and the piezoelectric force sensors. Both sensors are capable of detecting the fluctuations in the applied pressure and force around the pre-applied load. The simultaneous signals detected by the two sensors enable the quantification of the acoustic pressure and the lift force, in addition to the phase between them. This information can help identify the energy transfer between the acoustic power field and the forces on the cylinders by the fluid. For instance, data in figure 2 are recorded for a single cylinder at U = 49 m/s. The acoustic pressure is clearly correlated to the force on the cylinder, increasing and decreasing in magnitude with the same patterns. The two signals are out of phase at their dominant oscillating frequency.

Table 1 compares reported values of lift coefficient on a single cylinder in cross flow. The table shows data from investigations within comparable values of diameter

TABLE 1. DYNAMIC LIFT COEFFICIENT ON A SINGLE CYLINDER IN CROSS FLOW

Ref.	Asp. ratio	C_l
Mohany and Ziada [6]	3.0	0.24 - 0.28
Szepessy and Bearman [8]	6.7	0.30 - 0.53
West and Apelt [9]	10	0.46 - 0.61
Current Study	5.0	0.37 - 0.51

and aspect ratio, and within the same range of Reynolds number of 2×10^4 to 10^5. A full spectrum of related study of dynamic lift on a single cylinder, and the influence of the different parameters is exclusively reviewed by Norberg [10]. Values of dynamic lift coefficient measured off resonance agree with values reported for similar cases as shown in table 1. Moreover, measurements show that the lift force signals measured on the two sides of the cylinder are nearly in phase.

Figure 3 shows the frequency spectra of the acoustic pressure and the lift force on the three cylinders at a flow velocity of U = 40 m/s. This flow velocity does not cause a lock-in with the first acoustic mode of the duct. The acoustic pressure spectrum shows two distinct peaks, one at the vortex shedding frequency around 210 Hz, corresponding to a Strouhal number of 0.13 The second peak in the acoustic pressure spectrum is of a lower amplitude, at f = 660 Hz, related to the first acoustic cross mode weak excitation by the turbulence in the flow. The lift force spectra on the three cylinders show a distinctive peak at f = 210 Hz, at the vortex shedding component. The amplitude of the force on the upstream cylinder is significantly less than the dynamic force on the middle and downstream cylinders.

Figure 4 shows the aeroacoustic response of three

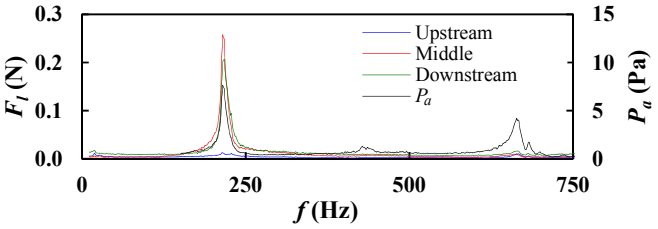


FIGURE 3. FREQUENCY SPECTRUM OF THE ACOUSTIC PRESSURE AND LIFT FORCE ON THREE INLINE CYLINDERS AT U = 40 M/S

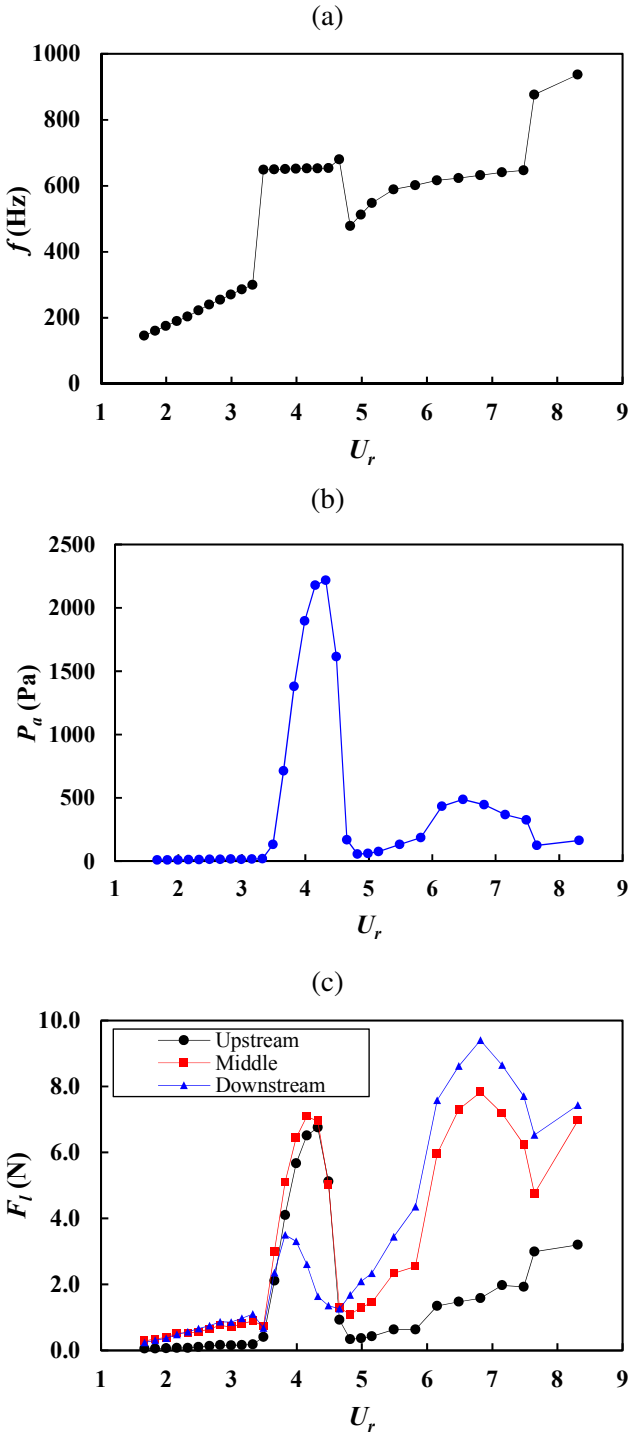


FIGURE 4. AEROACOUSTIC RESPONSE AND DYNAMIC LIFT FORCE ON THREE INLINE CYLINDERS IN CROSS FLOW.

cylinders arranged inline over a range of reduced flow velocities. Figure 4(a) shows the vortex shedding frequency. In the range up to U_r = 3.5, vortex shedding occurs at a frequency proportional to the flow velocity, which refers to a Strouhal number value of 0.13. For U_r in the range of 3.5 to 5.0, the frequency increases abruptly to a fixed value of about 650 Hz, an increase associated with an excitation of the first acoustic mode to an acoustic pressure of 2.2 kPa, equal to 160 dB, as shown in fig. 4(b). This sudden increase occurs prior to the coincidence between the vortex shedding frequency and the first acoustic cross mode, and is reported only for inline rows of more than one cylinder. The dynamic lift force on the three cylinders, shown in fig. 4(c) increases significantly during this range of flow velocities. The upstream and middle cylinders sustain rms lift forces increasing suddenly from 1.0 N up to 7.0 N. The rms lift force on the downstream cylinder increases to a lower value of 3.5 N. When the flow velocity further increases to values of U_r = 5.0 to 6.0, , the lock-in status between the first acoustic mode and the flow field ceases to exists, and the high acoustic pressure values no longer persist. Frequency of oscillation comes down to the linearly increasing values corresponding to the vortex shedding Strouhal number of 0.13. Upon further increase of the flow velocity, the frequency of vortex shedding increases until it coincides with the first acoustic mode frequency. At the value of U_r = 6.0, the coincidence between the two frequencies causes a second lock-in between the acoustic and the flow fields, supplying energy to a resonance condition. At U_r = 6.5, the acoustic pressure reaches a peak of 0.5 kPa, significantly lower than the pre-coincidence resonance peak. Dynamic lift force on the upstream cylinder does not increase significantly during the coincidence resonance range, in contrast with the significant increase described earlier during pre-coincidence. The middle cylinder experiences a significant increase in the rms lift force to a peak of 7.8 N at U_r = 6.8. Likewise, the downstream cylinder experiences the highest rms lift force increase to a peak of 9.4 N at the same reduced velocity.

The behavior of the lift force on the three cylinders during the two different regions of resonance suggests that two different mechanisms are responsible for the excitation of resonance. The significant increase in the lift force on the upstream and middle cylinders during the pre-coincidence resonance suggests that the sound source is located in the gap between them, creating nearly equal

sound-induced forces on the two cylinders. Flow regimes in the cavity between those two cylinders can excite resonance at flow velocities lower than those necessary for the wake vortex shedding to coincide with the first acoustic mode frequency. On the other hand, coincidence resonance results in significantly higher forces on the upstream cylinder, and the middle and upstream cylinders are affected to a lesser extent. This points toward the wake forming around the whole configuration of the three inline cylinder that sheds vortices at a Strouhal number of 0.13. The different strength of the pre-coincidence and coincidence sound sources is a result from their different location and origin phenomena.

CONCLUSION

In this study, the aeroacoustic response and the dynamic lift force on three inline cylinders in cross flow in a rectangular wind tunnel section are experimentally measured and discussed. The flow around the cylinders excites two distinctive regions of acoustic resonance at two different ranges of flow velocities. The earlier resonance occurs prior to the frequency coincidence between the vortex shedding downstream of the three cylinders and the first acoustic mode. At higher velocities, resonance occurs again when the vortex shedding frequency coincides with the first acoustic mode frequency. The lift force on the upstream and middle cylinder increases significantly during the pre-coincidence resonance, while the downstream cylinder is not significantly affected. This suggests that the sound source is located in the gap between the upstream and middle cylinders. In contrast, lift on the downstream cylinder is the most significantly increased during the coincidence resonance, while the two other cylinders also undergo lesser increase. Therefore, the sound source during the coincidence resonance is created by the alternating wake around the three cylinders. The two resonance regimes are fundamentally different, which is important consideration when trying to control flow excited acoustic resonance.

ACKNOWLEDGEMENTS

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REFERENCES

[1] S Ziada. Flow-excited acoustic resonance in industry. *Journal of Pressure Vessel Technology*, 132(1): 015001, 2010.

[2] M Shaaban and A Mohany. Parametric investigation of the flow-excited acoustic resonance from multiple in-line cylinders in cross-flow. In *ASME 2015 Pressure Vessels and Piping Conference*, 2015.

[3] A Mohany and S Ziada. Numerical simulation of the flow-sound interaction mechanisms of a single and two-tandem cylinders in cross-flow. *Journal of Pressure Vessel Technology*, 131(3):031306, 2009.

[4] A Mohany and S Ziada. Flow-excited acoustic resonance of two tandem cylinders in cross-flow. *Journal of Fluids and Structures*, 21(1):103–119, 2005.

[5] A Mohany and S Ziada. Effect of acoustic resonance on the dynamic lift forces acting on two tandem cylinders in cross-flow. *Journal of Fluids and Structures*, 25(3):461–478, 2009.

[6] A Mohany and S Ziada. Measurements of the dynamic lift force acting on a circular cylinder in cross-flow and exposed to acoustic resonance. *Journal of Fluids and Structures*, 27(8):1149–1164, 2011.

[7] M Shaaban and A Mohany. Flow-induced vibration of three unevenly spaced in-line cylinders in cross-flow. *Journal of Fluids and Structures*, 76:367–383, 2018.

[8] S Szepessy and P W Bearman. Analysis of a pressure averaging device for measuring aerodynamic forces on a circular cylinder. *Experiments in fluids*, 16(2):120–128, 1993.

[9] G S West and C J Apelt. Measurements of fluctuating pressures and forces on a circular cylinder in the reynolds number range 104 to $2\cdot 5\times 105$. *Journal of Fluids and Structures*, 7(3):227–244, 1993.

[10] C Norberg. Fluctuating lift on a circular cylinder: review and new measurements. *Journal of Fluids and Structures*, 17(1):57–96, 2003.