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PVP2021-62696

THE AEROACOUSTIC RESPONSE OF A SINGLE SQUARE CYLINDER IN CONFINED CROSS FLOW

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ABSTRACT

Unstable flow patterns around arrangements of bluff bodies in different engineering applications can give rise to pressure oscillations, leading to excitation of strong acoustic resonance that can interrupt operation. In certain conditions, flow fluctuations arising from vortex shedding downstream of a circular cylinder are reported to excite severe acoustic resonance. On the other hand, cylinders of a square cross section are known to be particularly susceptible to mechanisms that involve coupling between the flow and a structural mode. It is not documented, however, if such coupling would occur between an acoustic mode and flow fluctuations downstream of a square cylinder. In this work, the possibility of excitation of acoustic resonance due to coupling between unsteady flow downstream of a single square cylinder with an acoustic cross mode of a rectangular duct is experimentally investigated. During the experiments, acoustic resonance was self-excited. Measurements of the acoustic pressure and the flow velocity are carried out for a single square cylinder of an edge length of 25.4 mm. Results show that aeroacoustic response characteristics for this configuration are not completely analogous to the case of a circular cylinder, with a number of features not reported before. A brief summary of the results is presented in this work.

1 INTRODUCTION

Periodic flow instabilities are know to be susceptible to excitation of severe resonant acoustic tones that arise as a result of coupling between the flow and the acoustic fields. Such tones have been reported in a vast variety of applications including shear flow over cavities [1–3], impinging jets [4], heat exchanger tube bundles [5], steam generators [6], and many other configurations [7–10]. At certain conditions, severe noise levels associated with the self-excitation of resonance are often observed and accompanied with excessive vibration and sound pressure levels, which may result in interruption of operation or failure of equipment [11].

The self-excitation of acoustic resonance by fluid flow over cavities and bluff bodies is a result of a fluid-resonant coupling mechanism that transfers energy between the acoustic and flow fields. At subcritical Reynolds numbers, the flow field around a bluff body results in alternating vortex shedding at a frequency proportional to a characteristic cross-section length L, and the incoming flow velocity U_∞. This periodic fluctuation in the flow field is accompanied by pressure and flow velocity fluctuations that occur at the same frequency f_v, characterized by the Strouhal number defined as

$$St = \frac{f_v L}{U_\infty} \tag{1}$$

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In many applications, the flow is confined in a surrounding system with solid walls with a fundamental acoustic mode frequency f_a that depends on the domain dimensions and not significantly on the flow velocity. Therefore, a coincidence of frequencies can occur between the flow and acoustic fluctuations at certain flow velocities. If the perturbation of flow velocity due to the flow instability is oriented in the same direction as the acoustic particle velocity of such mode, a transfer of energy becomes likely. At flow velocity that causes frequency coincidence, the acoustic field gains energy and the self-excited oscillations grow stronger. The stronger acoustic field and the periodic flow oscillation lock-in and occur at exactly the same frequency, and the flow instability is enhanced into a more organized form with more energy. This feed-back flow of energy completes a viscous cycle that results in severe oscillations, much stronger than the weak noise often observed in non-confined conditions.

Flow-excited acoustic resonance has been observed to occur in several different configurations, such as a single cylinder [12], tandem cylinders [13, 14], closely-packed arrays [15–17], side-by-side cylinders [18] inline arrangements of cylinders [19,20], with different mechanisms in play. Ziada et al. [15] reported that closely-packed arrays of cylinders are capable of excitation of acoustic resonance due to certain flow instability, where as other instabilities are not able to excite acoustic resonance. For a single cylinder in cross flow, the mechanism of resonance excitation was attributed to the vortex shedding downstream of the cylinder [21, 22]. Mohany and Ziada [12] showed that the orientation of the acoustic mode, as well as the phase between the flow and the acoustic cycle are crucial to result in net acoustic energy production over a cycle of acoustic resonance.

Structures of square cross sections are often used as supports and struts in many engineering applications. When exposed to fluid flow, the hydrodynamic disadvantages of sharp-edged square cross-sections, particularly their susceptibility to flow-induced vibration, are well-known [23]. As other design considerations, such as economic aspects, structural requirements, and the ease of assembly can make it feasible to develop designs using this particular structure configuration, fluid-dynamic considerations have been investigated and accurately documented to provide knowledge for designers to avoid the occurrence of vortex-induced vibration [24]. However, these structures are likely to be susceptible to fluid-resonant mechanisms that lead to resonance self-excitation. The necessary knowledge of the Strouhal numbers and the characteristics of flow-acoustic interaction that may lead to excitation of acoustic resonance are not reported in literature. Okajima [25] observed that the Strouhal number for periodic vortex shedding downstream of a single square cylinder with a zero angle of attack shows a significant dependence on Reynolds number . Moreover, cylinders with sharp edges shed vortices at lower Strouhal numbers. Although structures of cross section are used in various applications that involve confined cross-flow, there are no information regarding the nature of the potential interaction between the acoustic mode and vortex shedding. Information regarding the aeroacoustic response of this simple configuration is not yet available. Such knowledge is needed to safeguard designs against the possibility of a potentially damaging excitation of acoustic resonance at certain flow velocities. Therefore, this work provides an experimental investigation of the aeroacoustic response of a single square cylinder confined in a rectangular duct in cross flow. The acoustic pressure development with the flow velocity, as well as the frequency of the dominant mode in the pressure spectra are reported. The flow condition for potential self-excitation of acoustic resonance is reported in terms of the normalized flow velocity. This information can be used to predict the flow velocity at which acoustic resonance can occur in a design that involves a single square cylinder. A brief summary of the results is provided.

2 EXPERIMENTAL SETUP

Figure 1 shows a simplified schematic of the test section used to measure the aeroacoustic response. Experimental measurements were carried out in an open-loop wind tunnel. Air flow into the test section is driven by a centrifugal blower located at the downstream end of the wind tunnel. Uniform air flow is drawn into the wind tunnel through a bell-mouth. The cross-section of the test section is rectangular with a width B = 127 mm and a height H = 254 mm. The dimensions of the test section are kept constant to avoid changing the acoustic attenuation due to visco-thermal losses [26, 27]. The length of the test section is sufficiently long in order to minimize acoustic radiation losses through the inlet and outlet boundaries. The subsequent diffuser section is connected to the air blower using a flexible duct connection to isolate vibration between the blower and the wind tunnel. The maximum achievable air velocity was around 150 m/s, equivalent to a Mach number of 0.43, with a maximum uncertainty of $\pm$ 2.3%.

A single cylinder of square cross-section is attached horizontally from side-to-side in the middle of the test section height. The flow perturbation due to the vortex shedding downstream of the cylinder occurs in a direction normal to both the cylinder axis and the flow direction. Moreover, flow perturbation can only excite acoustic modes with non-zero vertical acoustic particle velocity at the horizontal center-line plan, leading to potential excitation of the first and the third acoustic cross-modes, but not the second. The square cylinder has an edge length l = 25.4 mm, causing a flow blockage of 10%, leading to conditions of potential self-excitation of acoustic resonance. Inlet flow velocity is measured using a Pitot tube, which is used to calibrate the wind tunnel air drive frequency, and is not used during self-excitation of acoustic resonance to avoid any interference with the flow and acoustic modes. The theoretical frequency of the first transverse acoustic mode in the wind tunnel with no cylinders installed is $f_a = c/2H$ = 675 Hz, where c is the speed of sound in air.

To evaluate the aeroacoustic response of the square cylinder, the acoustic pressure is measured at different inlet flow velocities. Acoustic pressure measurements are carried out using a 1/4 inch pressure microphone, flush mounted

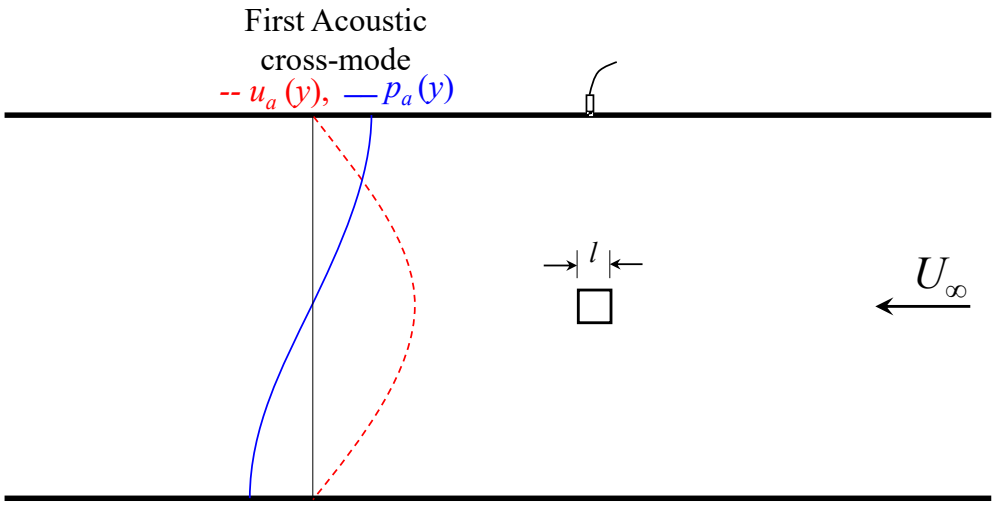


FIGURE 1. Configuration of the experimental setup showing the distribution of the acoustic pressure and acoustic particle velocity for the first acoustic cross-mode of the duct.

at the top boundary of the test section. The microphone is therefore attached at the antinode of the acoustic pressure corresponding to the excited acoustic cross modes. The microphone is attached exactly above the axis of the cylinder as shown in figure 1. The pressure signal is recorded for a duration of 120 s at a sampling frequency of 20 kHz. To calculate the root mean square acoustic pressure (p_a), the microphone signal is filtered using a high pass filter with cut-off frequency of 60 Hz to isolate any electric noise. Acoustic root mean square pressure values are determined with a maximum uncertainity of $\pm$ 0.93%. The frequency spectrum is calculated using the Welch's modified periodogram method with 50% overlap and 1.0 Hz frequency resolution, and an uncertainity of $\pm$0.5 Hz.

3 RESULTS

Figure 2 shows the aeroacoustic response of a single cylinder with a square cross section in cross flow. At low flow velocities, the frequency increases linearly as the flow velocity increases. In this range, the frequency corresponds to a Strouhal number of St = 0.14, which agrees well with the observations for a single cylinder of a square cross section in external cross-flow. At a flow velocity of U_∞ = 70 m/s, the frequency increases upruptly to around 1950 Hz, equivalent to the frequency of the third acoustic mode. This increase is accompanied by an increase in the acoustic pressure, indicating the self-excitation of acoustic resonance at the frequency of the third acoustic mode. Similar abrupt increases in frequency and acoustic pressure were reported for arrangements of inline cylinders, and were excited by a mechanism of separation and impingement over the gap between cylinders [19, 20, 28]. However, The presented results are for a case with a single cylinder, with no gap flow. The Strouhal number of this resonance episode based on the side length is close to 0.55, which is close

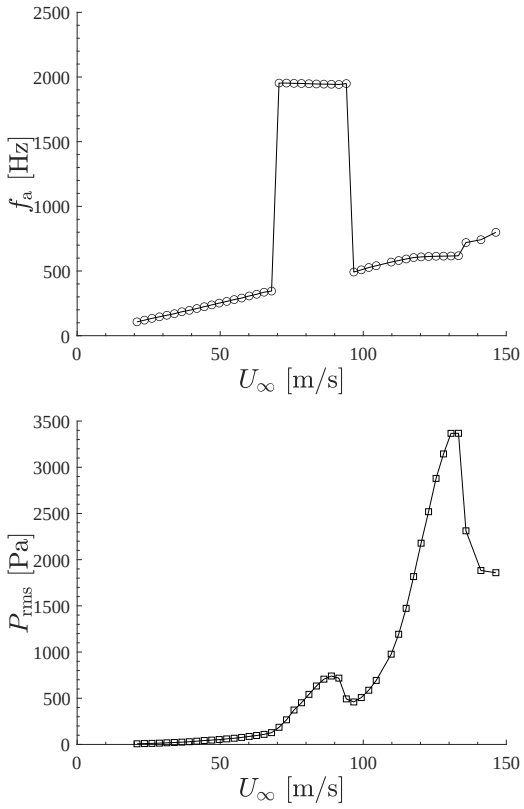


FIGURE 2. The aeroacoustic response of the a single square cylinder in cross-flow.

to the Strouhal number observed for flow over a cavity with the same characteristics length between the separation and impingement points. This suggests that the exciting periodic flow may be the separation of the flow at the sharp leading edge and the impingement on the sharp trailing edge, which would not occur without the influence of the

acoustic resonance excitation. A further increase of the flow velocity beyond U_∞ ends the excitation episode of the third acoustic cross mode. The acoustic pressure is reduced and the dominant frequency falls back to the linear increase according to the Strouhal number $St = 0.14$. At a slightly higher flow velocity, coincidence between the vortex shedding frequency and the first acoustic cross-mode frequencies occurs as expected. The coincidence triggers another increase in the acoustic pressure, up to significantly higher levels due to the abundance of flow energy. The acoustic pressure reaches close to 3.3 kPa and results in lock-in of the two frequencies at a value of 668 Hz. Increasing the flow velocity ends this lock-in region.

Figure 3 shows the spectral characteristics of the aeroacoustic pressure at an inlet flow velocity of $U_\infty = 70$ m/s. At this flow velocity, the coressponding shedding frequency is 382 Hz, equivalent to a Strouhal number $St = 0.14$, in close agreement with values reported for a square cylinder in cross flow with an incident flow angle of 0° at similar Reynolds numbers [29]. The spectrogram shows a persistent peak at 382 Hz, corresponding to the vortex shedding peak over the time of the sample. The frequency of vortex shedding is stable and concentrated in a narrow band of frequencies. Figure 3b shows a peak corresponding to the first acoustic cross mode frequency at 669 Hz. This peak occurs at significantly lower acoustic pressure levels, with p_a less than 5 Pa. As the flow velocity increases, the vortex shedding peak f_v increases in frequency and moves closer to the value of the acoustic mode peak f_a.

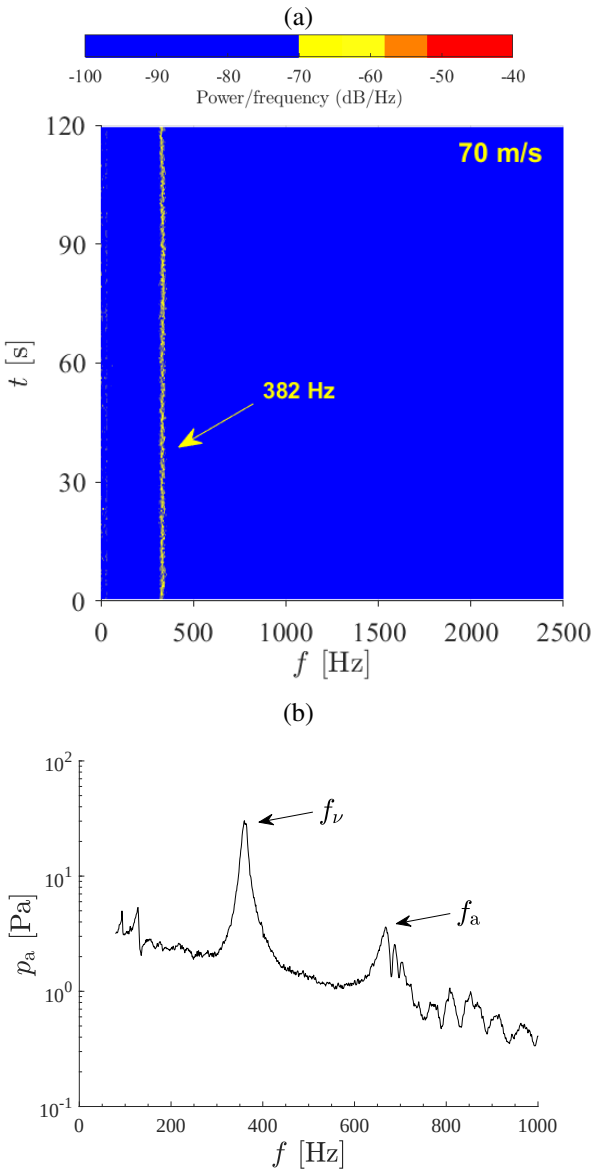


FIGURE 3. Spectral characteristics of the acoustic pressure at a flow velocity lower than necessary for excitation of the first acoustic mode. (a) Time spectrogram (b) Overall frequency content.

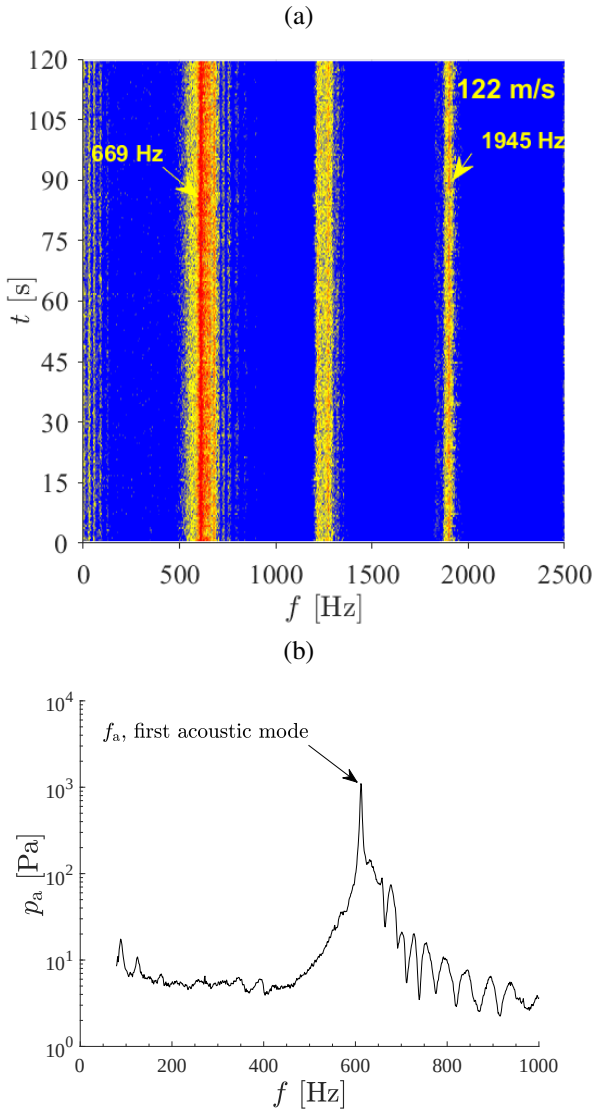


FIGURE 4. Spectral characteristics of the acoustic pressure during excitation of resonance at the first acoustic cross-mode. (a) Time spectrogram (b) Overall frequency content.

At a flow velocity of $U\infty = 122$ m/s, vortex shedding occurs at a frequency of 669 Hz, coinciding exactly with

the first acoustic cross-mode frequency. The spectrogram of this signal, figure 4a, shows various peaks that are persistent over the signal duration of 120 s. The tonal peak at 669 has a sharp peak that has a higher power spectral density than other peaks of higher frequencies. Morever, figure 4b shows that at this condition, the spectra shows a significant increase in acoustic pressure at the frequency of the first acoustic cross-mode. The acoustic pressure at this flow velocity is tonal, with energy concentrated at a small band of frequencies. Lock-in between the acoustic and flow fields result in a severe sound pressure. The root mean square pressure at this flow velocity reaches P_{rms} = 3.3 KPa, equivalent to 164 dB. This value is significantly higher than those observed for a single circular cylinder with a diameter equal to the edge length of 25.4 mm. Due to the lower Strouhal number, the coincidence of the vortex shedding frequency leads to coincidence at a higher flow velocity, providing the flow with much higher energy input during resonance. The different flow around the cylinder also is expected to have a significant role in determining the mechanism by which energy is transferred, and the resulting sound pressure level.

Figure 5 shows the spectral characteristics of the pressure signal at a flow velocity of U_∞ = 88 m/s. This flow velocity is selected for being at the peak of the peculiar excitation of acoustic resonance at the frequency of the third acoustic cross-mode at relatively low flow velocities. The spectrogram of the signal shows several peaks of different power spectral density at different frequencies. Two frequencies stand out as dominant in their ranges, the vortex shedding frequency at 423 Hz, and the third mode frequency at 1945 Hz. Figure 5a shows that the acoustic pressure level at the peak of this lock-in region is close to 1.0 kPa and the dominant frequency is locked-in at 1945 Hz. The sudden excitation of acoustic resonance at higher frequencies than the dominant vortex shedding frequency has been reported for other configurations, such as two tandem cylinders, and was attributed to a different periodic instability than the von-Karman shedding [19, 30]. In addition to the tone of the acoustic resonance, the spectrum of the pressure signal shows the presence of the vortex shedding frequency f_ν at a value lower than 500 Hz. This suggests that the vortex shedding flow pattern downstream of the cylinder is not directly responsible for self-excitation of this acoustic resonance region. The weak peak of the first acoustic mode can be also observed, not excited by any significant coupling mechanism, but by turbulent energy in flow.

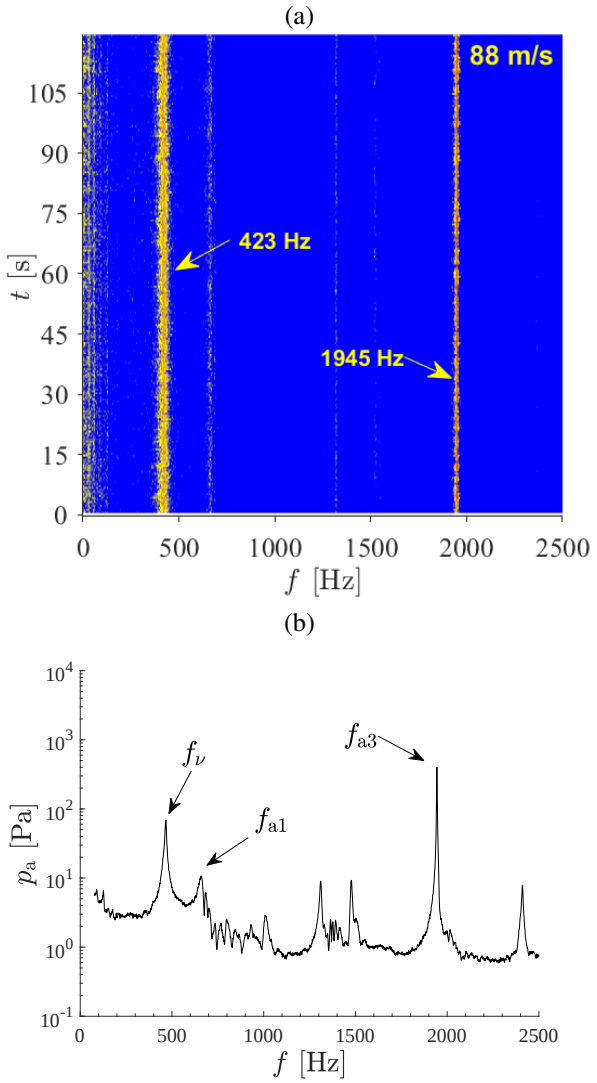


FIGURE 5. Spectral characteristics of the acoustic pressure at a flow velocity lower than necessary for excitation of the third acoustic mode. (a) Time spectrogram (b) Overall frequency content.

4 CONCLUSION

In this work, the aeroacousic response of a single cylinder with a square cross-section when placed in confined air cross-flow is presented. A cylinder of a square cross section with an edge length of 25.4 mm was fixed in a duct with a height of 254 mm, with its axis normal to the flow direction and the plane of the acoustic particle velocity for acoustic cross-modes. The cylinder was tested in uniform air cross-flow of velocities up to 150 m/s. Results show that unlike the case of a single circular cylinder, the present configuration induces self-excitation of strong acoustic resonance of the third acoustic mode at a relatively low flow velocity. At higher flow velocities, self-excitation of the first acoustic cross-mode is observed. During acoustic resonance excitation, lock-in of frequencies is observed, accompanied by a significant increase in sound pressure level. Acoustic resonance of a maximum acoustic pressure P_{rms} = 3.3 kPa was observed. The Spectral characteristics of the two different episodes of resonance self-excitation indicate two different excitation mechanisms.

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