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Effect of Flow Impingement on the Acoustic Resonance Excitation in A Shallow Rectangular Cavity

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ABSTRACT

Flow-excited acoustic resonance in cavities can produce a high level of acoustic pressure that may lead to severe damage. This occurs as the flow instability in the cavity, which is created by the free shear layer separation at the cavity upstream edge, is coupled with one of the acoustic resonance modes in the accommodating enclosure. This flow instability is sustained and organized by the perturbations that propagate from the downstream edge to the upstream edge due to the flow impingement at the downstream edge of the cavity. The characteristics of this flow impingement significantly influence the feedback cycle of the flow-excited acoustic resonance. By interrupting this feedback cycle, the acoustic resonance excitation may be attenuated. This paper considers the effect of the downstream edge geometry on the acoustic resonance excitation in a rectangular cavity with an aspect ratio of 1.0. Several edges, including chamfered edges with different angles, round edges with different radii, tooth edges, cylinders, higher and lower steps, and spoilers, are investigated to address the effect of the downstream flow impingement on the acoustic resonance excitation in the cavity and Strouhal number values. The experiments are conducted in an open loop wind tunnel that can generate a flow with a Mach number up to 0.45. The results of each case are compared with a base case where sharp edges are installed upstream and downstream. It is observed that some edges are able to noticeably reduce the acoustic pressure; moreover, a shift in the resonance excitation to higher velocities is observed. The Strouhal number values are compared for several cases with different upstream and/or downstream edges to address the relation between the cavity geometry and Strouhal number values.

NOMENCLATURE

c	Speed of sound [m/s]
D	Depth of the cavity [m]
f	Frequency of dominant shear layer oscillations [Hz]
H	Height of the test section [m]
L	Length of the cavity [m]
N	Number of Shear layer mode
n	Number of acoustic mode
St	Strouhal number
U	Mean flow velocity [m/s]

INTRODUCTION

Flow over cavities is a design concern in many engineering applications, such as aircraft weapon bays (Rossiter and Kurn, 1962; Lawson and Barakos, 2011), side branches in piping systems and HVAC (Brugeman et al., 1991; Knotts and Selamet, 2003), and valves. When flow passes over a cavity, a boundary layer separation at the cavity upstream edge occurs and results in the formation of a shear layer over the cavity mouth, as shown in Figure 1. The shear layer formation creates vortices that are carried with the flow to impinge on the downstream edge of the cavity. The impingement of these vortices on the downstream edge generates pressure perturbations at the downstream edge of the cavity. These perturbations travel back upstream to enhance the shear layer separation and close a feedback cycle of oscillations. The sound wave coupling with the flow oscillations creates a phenomenon known as the flow-excited acoustic resonance (Rockwell and Naudascher, 1978; Gloerfelt, 2009; Rockwell et al., 2003; Mohany and Ziada, 2005; Shaaban and Mohany, 2015). This phenomenon can result in a high level of acoustic pressure that may lead to catastrophic damage of the equipment.

Acoustic resonance in cavities can be suppressed using passive methods, such as modifying the cavity geometry (Baldwin and Simmons, 1986; Knotts and Selamet, 2003; Bruggeman et al., 1991), placing a control cylinder near to the upstream edge (Keirsbulck et al., 2008; Illy et al., 2008; Omer and Mohany, 2014), and adding spoilers or a block to the upstream edge (Omer et al., 2014; Shaaban and Mohany, 2015; Bolduc et al., 2013). One of the methods which is the subject matter of this work is the effect of the downstream edge on the acoustic resonance excitation in cavities. The geometry of the downstream edge controls the flow impingement, which in turn influences the feedback oscillation cycle; moreover, the mass addition into the cavity is affected as well.

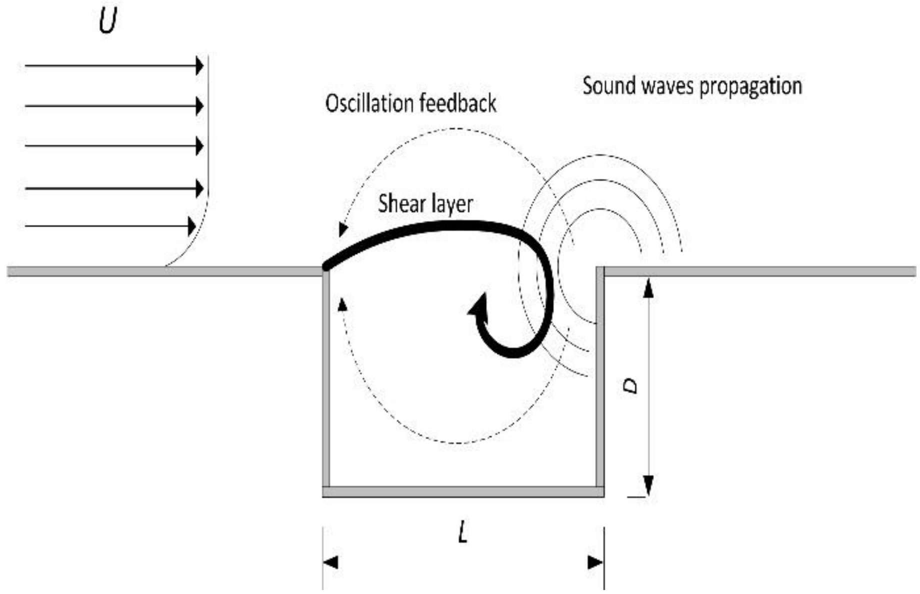

FIGURE 1: SCHEMATIC OF FLOW OVER CAVITY AND PROPAGATION OF SOUND

Heller and Bliss (1975) suggested that cavity oscillations are generated due to mass exchange resulting from the interaction at the downstream edge of the cavity. The mass addition and removal process creates a pressure wave that travels upstream, and it can be resembled by piston movement installed at the downstream edge of the cavity. One method used to mitigate these oscillations is to modify the downstream edge geometry to alter the mass exchange process. Heller and Bliss (1975) investigated a chamfered downstream edge combined with/without a spoiler in the upstream. The edge was found to be effective in suppressing the resonance; however, the effect of the chamfering angle on the resonance and the Strouhal number values was not considered. Zhang et al. (1998) computationally investigated the effect of the downstream edge on the cavity oscillations in a supersonic flow by investigating rounded and chamfered edges. They found that these geometries are able to reduce the pressure oscillations; moreover, a reduction in the cavity drag can be achieved by using these geometries. Recently, Vikramaditya and Kurian (2014) studied the effect of the downstream edge geometry on the pressure perturbations in a supersonic flow. Different types of chamfered edges were investigated, including chamfering the entire depth of the cavity, and they were found to be effective in mitigating the pressure perturbations in the cavity. However, most of the previous works were performed at off resonance conditions and it is not clear whether altering the flow impingement of the shear layer in the cavity can be used effectively to disrupt the feedback cycle of oscillations and hence control the acoustic resonance excitation. Therefore, the main objective of this paper is to investigate the effect of the flow impingement at the downstream edge of the cavity on the acoustic resonance excitation. Several geometries of downstream cavity edges, including geometries that were not investigated in the literature, are investigated to address the influence of the edge geometry on the resonance excitation and the Strouhal number values.

EXPERIMENTAL SETUP

The experiments were conducted in an open loop wind tunnel. The setup consists of a 254 mm high and 127 mm wide test section made of 25.4 mm thick acrylic sheets, as shown in figure 2. The cavity has an aspect ratio of 1.0 with dimensions of 127 × 127 × 127 mm, and the cavity is attached at 330 mm from the test section inlet. At the inlet the test section is attached to a bellmouth that stabilizes the flow and reduces the pressure drop at the inlet. The cavity was designed with the ability to change both the upstream and downstream edges independently. The air flow is generated by means of a centrifugal blower connected to the test section through a diffuser. The centrifugal blower is driven by a 75 horsepower motor and can produce a flow with a maximum flow velocity of 155 m/s with a turbulence level less than 1%. The instrumentation in the experiments consists of a pressure microphone flush mounted at the cavity floor to measure the maximum acoustic pressure of the acoustic cross modes. The experiments were repeated for some cases several times to assure the consistency of the results. A LabVIEW program was used for the data acquisition and analysis with a sampling rate of 10 kHz, and each signal was averaged 60 times which corresponds to 60 seconds in real time. Different edges were installed downstream of the cavity and the results for each case was compared to the base case where a sharp edge is installed downstream. The edges investigated are: a sharp rectangular edge, round edges with two different radii (25.4 mm and 12.7 mm), chamfered edges with four angles (107°, 120°, 135° and 150°), a saw-tooth edge, straight and delta spoilers, higher and lower steps, and a cylinder attached close to the downstream edge. The dimensions and configurations of the edges are illustrated in figure 3 to figure 6.

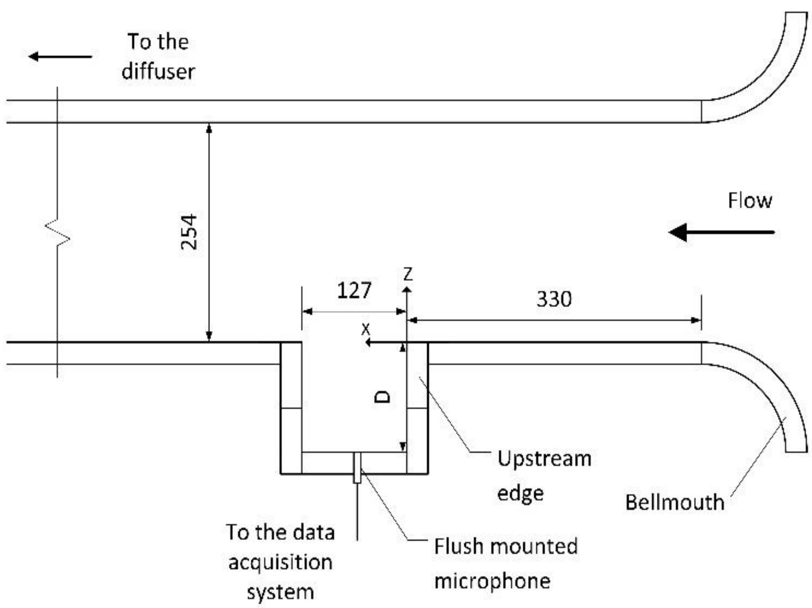

FIGURE 2: SCHEMATIC DRAWING OF THE TEST SECTION (ALL DIMENSIONS IN mm)

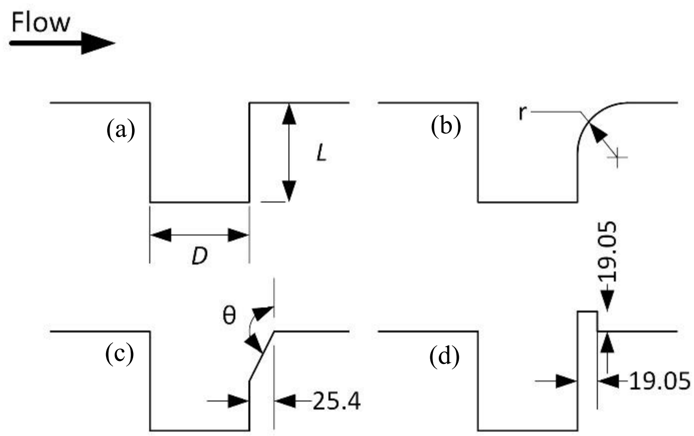

FIGURE 3: (a) BASE CASE SHARP EDGES, (b) ROUND EDGES, (c) CHAMFERED EDGES, (d) HIGH STEP EDGE (ALL DIMENSIONS IN mm)

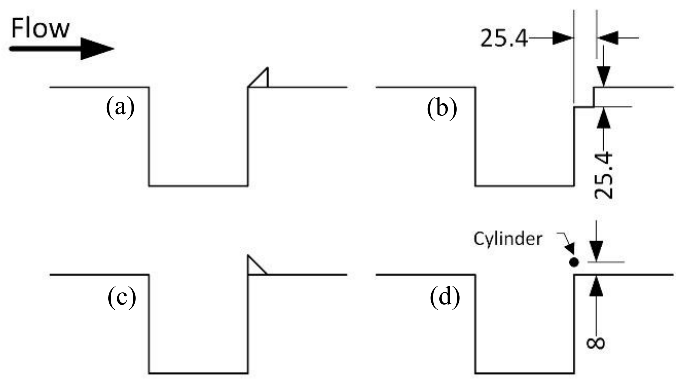

FIGURE 4: (a) SPOILERS TIP DOWNSTREAM, (b) LOW STEP EDGE, (c) SPOILERS TIP UPSTREAM, (d) CYLINDER (ALL DIMENSIONS IN mm)

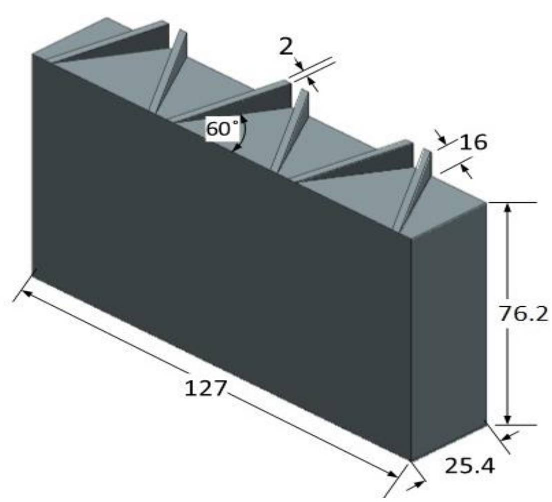

FIGURE 5: DELTA SPOILERS (ALL DIMENSIONS IN mm)

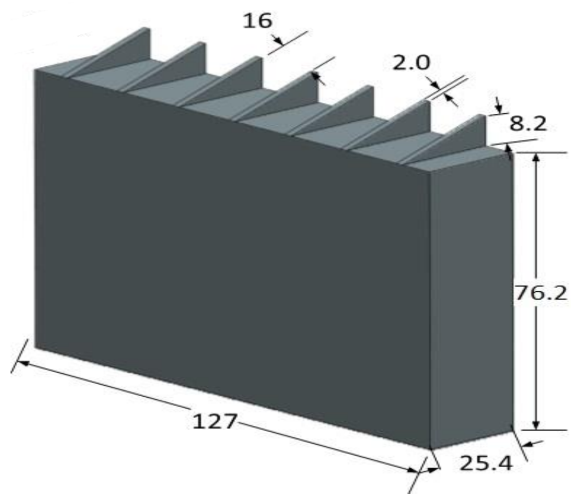

FIGURE 6: STRAIGHT SPOILERS (ALL DIMENSIONS IN mm)

RESULTS

In this section the results obtained are presented and discussed. The effect of the tested configurations at the downstream edge of the cavity are compared to the base cavity case, with shape edges installed both upstream and downstream. The base case is observed to excite three shear layer modes as illustrated in the waterfall plot in figure 7. Each line in this waterfall plot represents a pressure spectrum at a specific flow velocity starting from 0 to 155 m/s. The three shear layer modes excite the first acoustic cross mode. This occurs as the shear layer mode frequency approaches the acoustic cross mode frequency..The flow-excited acoustic resonance is therefore initiated and a lock-in region is observed. The first acoustic cross mode is observed to be the dominant mode and it generates the highest acoustic pressure values; hence, the comparison between the different configurations is performed with respect to the acoustic pressure of the first acoustic cross mode. The values of the acoustic pressure and the frequency of the dominant oscillations are extracted from the waterfall plot and depicted in figure 8. This figure shows that the acoustic pressure reaches 2000 Pa when the first acoustic cross mode is excited by the first shear layer mode. This occurs at a flow velocity of 127 m/s and a frequency of 464 Hz.

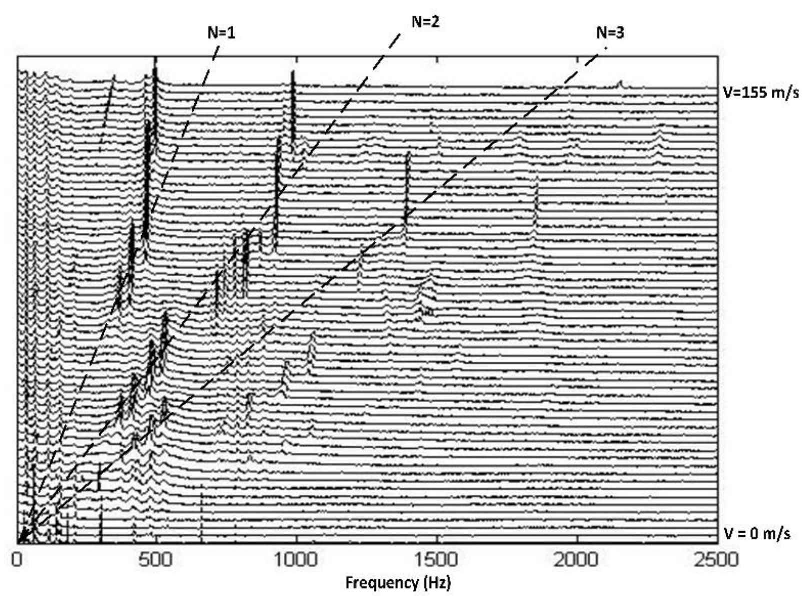

FIGURE 7: 2D WATERFALL PLOT FOR THE BASE CAVITY CASE WITH ASPECT RATIO OF 1.0

Different chamfered edges are investigated in different configurations. Figure 9 shows the acoustic pressure when the chamfered edges with different angles are installed at the downstream edge of the cavity. It can be seen that the acoustic pressure is noticeably reduced in some cases, compared to the base cavity with sharp edges. The resonance excitation is observed to be dependent on the angle of the chamfered edge. The acoustic pressure is observed to reduce as the angle of the chamfered edge increases. This occurs until an angle of 135˚, and increasing the angle further results in the opposite effect. This indicates that an angle of 135˚ is the best angle among the chamfered edges that can be used to reduce acoustic resonance when the edge is installed downstream. Moreover, it is observed that the resonance excitation is shifted to higher velocities. This shift is observed to be dependent on the angle of the chamfered edge as well. In general, increasing the angle of the chamfered edge results in a further shift in the acoustic resonance excitation to higher velocities. As the frequency of the acoustic cross mode remains constant, the Strouhal number values vary for each case due to the shift in the resonance excitation. This can be adapted by considering an effective length in the Strouhal number formula. This effective length should take the chamfer angle into consideration. The Strouhal number values and the effective length of the cavity will be discussed later.

In an earlier work, Omer et al. (2014) found that contrary to the downstream edge effect, chamfering the upstream edge results in intensifying the acoustic pressure values during resonance. It was also found that the delay in the resonance excitation is independent of the chamfered angle. These different behaviors can be attributed to the fact that the upstream edge controls the shear layer formation while the downstream edge controls the flow impingement and the feedback cycle.

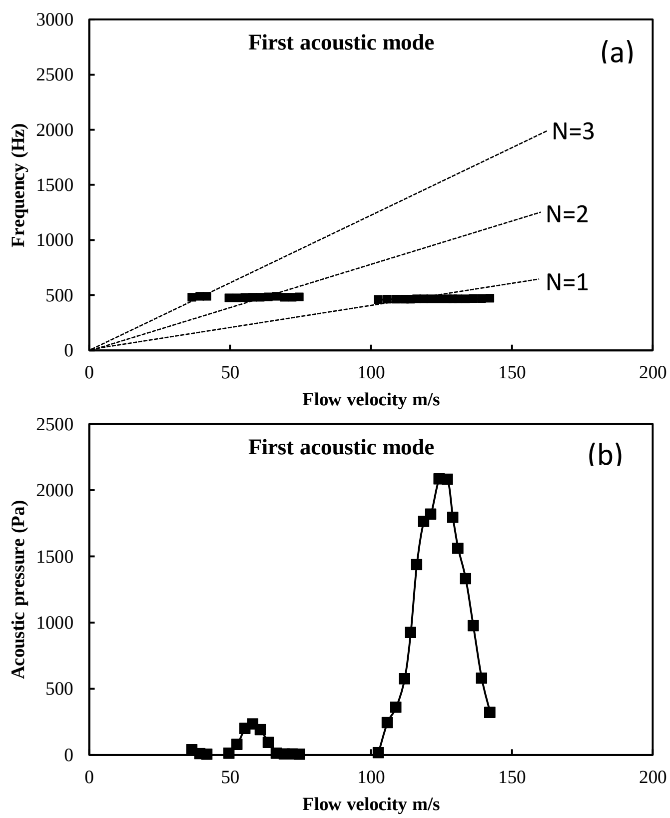

FIGURE 8: FIRST ACOUSTIC CROSS MODE EXCITED IN THE BASE CASE WITH ASPECT RATIO OF 1.0. (a) SHOWS THE FREQUENCY WITH THE FLOW VELOCITY, (b) SHOWS THE ACOUSTIC PRESSURE WITH THE FLOW VELOCITY

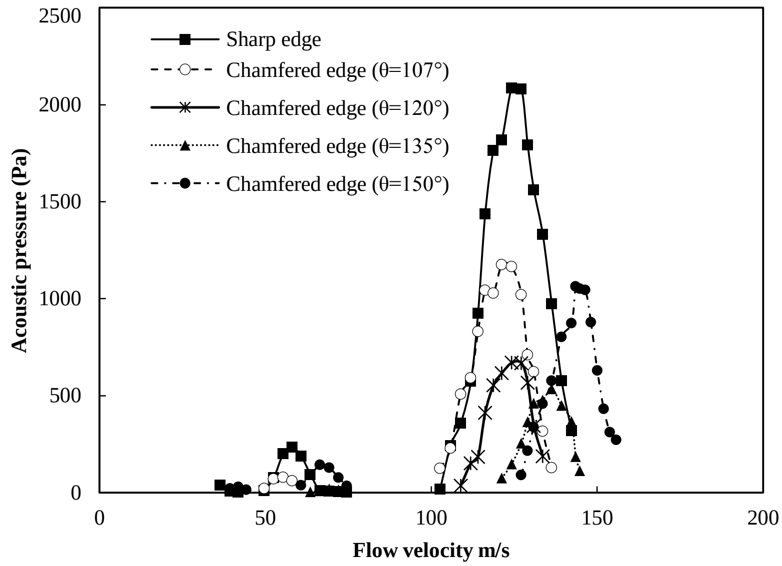

FIGURE 9: COMPARISON BETWEEN SHARP EDGE AND CHAMFERED EDGES

To compare the effect of chamfering the upstream and/or the downstream edge of the cavity, figure 10 shows the effect of chamfering the edge by an angle of 120˚. It can be seen that the acoustic pressure is significantly intensified when only the upstream edge is chamfered. However, chamfering the upstream and the downstream edge results in acoustic pressure values that are in the range between the corresponding values where only the upstream or the downstream edge is chamfered. Similar behavior is observed with the angles of 135˚ and 150˚, as shown in figure 11 and figure 12. It can be concluded from these figures that the shift in the acoustic resonance excitation is significantly influenced by which edge is chamfered. It is also noteworthy that chamfering the upstream and the downstream edge results in a further shift in the resonance excitation as the effective cavity length increases compared to either case alone.

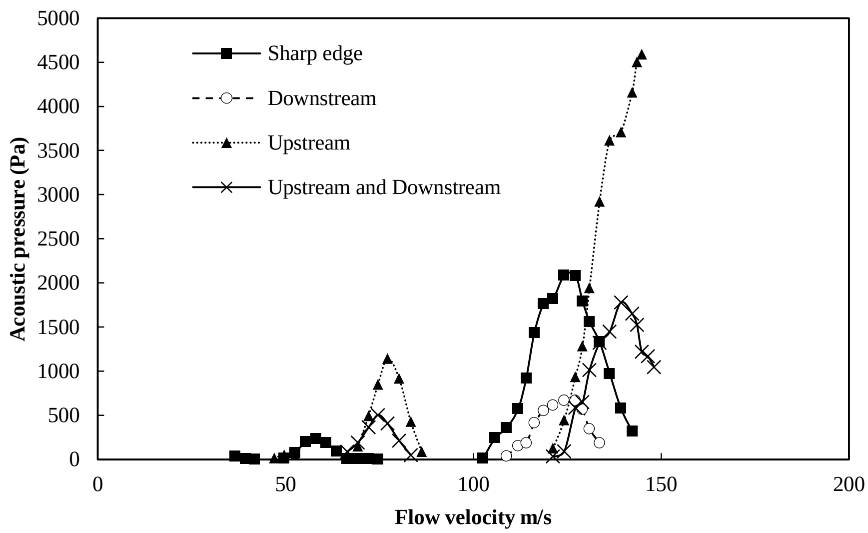

FIGURE 10: THE EFFECT OF CHAMFERING THE UPSTREAM AND/OR THE DOWNSTREAM EDGE BY 120˚

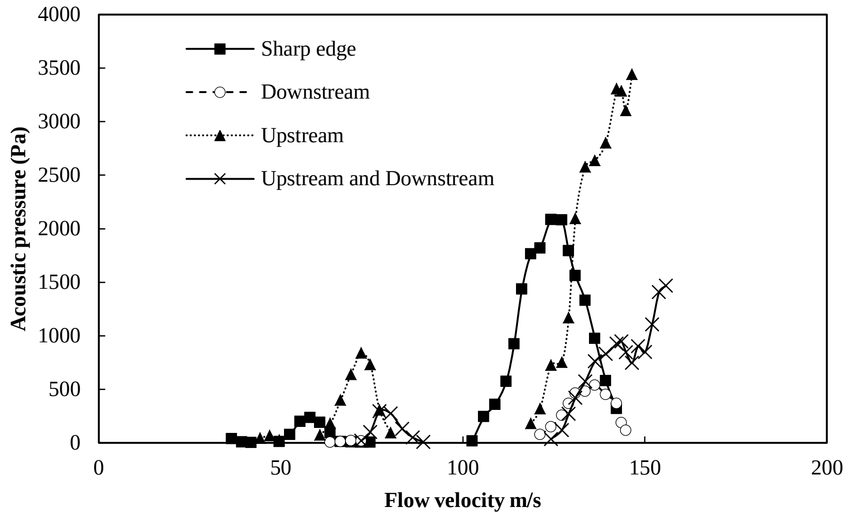

FIGURE 11: THE EFFECT OF CHAMFERING THE UPSTREAM AND/OR THE DOWNSTREAM EDGE BY 135˚

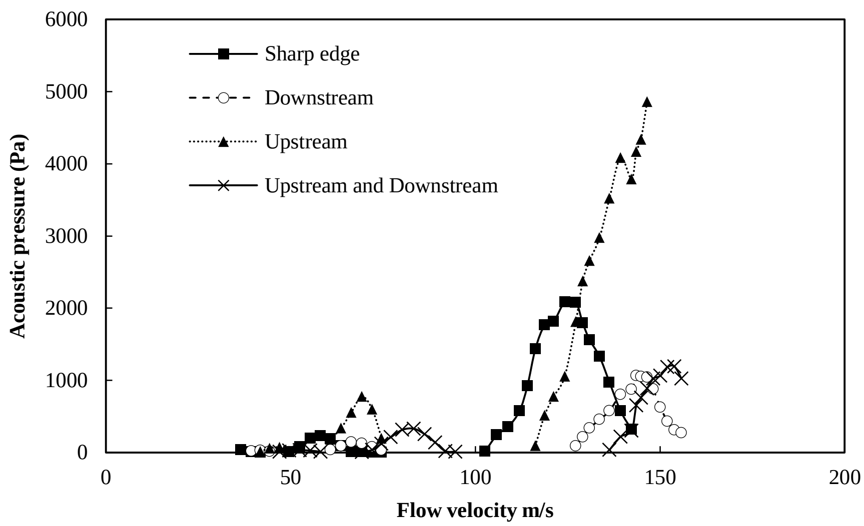

Figure 12: THE EFFECT OF CHAMFERING THE UPSTREAM AND/OR THE DOWNSTREAM EDGE BY 150˚

To further investigate the geometry effect on the acoustic resonance excitation, round edges with two different radii were tested. Figure 13 shows the effect of rounding the edges by a 12.7 mm radius. Similar to chamfering the edges, it is observed that the acoustic pressure is reduced when only the downstream edge is rounded. Furthermore, when both upstream and downstream edges are rounded, the acoustic pressure reaches values that are between the other two cases. Interestingly, rounding the downstream edge has no significant effect on shifting the acoustic resonance excitation to higher velocities. Moreover, rounding the upstream and the downstream edges has no clear difference from the case where only the upstream edge is rounded. Similar findings are observed when rounding the downstream edge by a radius of 25.4 mm. For this case the acoustic pressure is further reduced as shown in figure 14. In general, increasing the radius of the rounded edges upstream results in increasing the shift of the acoustic resonance excitation to higher velocities; however, rounding the downstream edge results only in reducing the acoustic pressure without shifting the resonance to higher velocities.

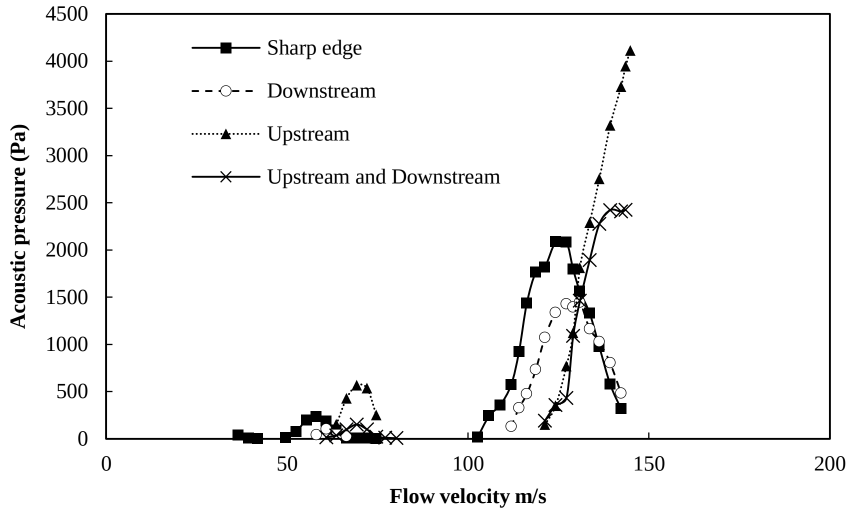

FIGURE 13: THE EFFECT OF ROUNDING THE UPSTREAM AND/OR THE DOWNSTREAM EDGE BY r = 12.7 mm.

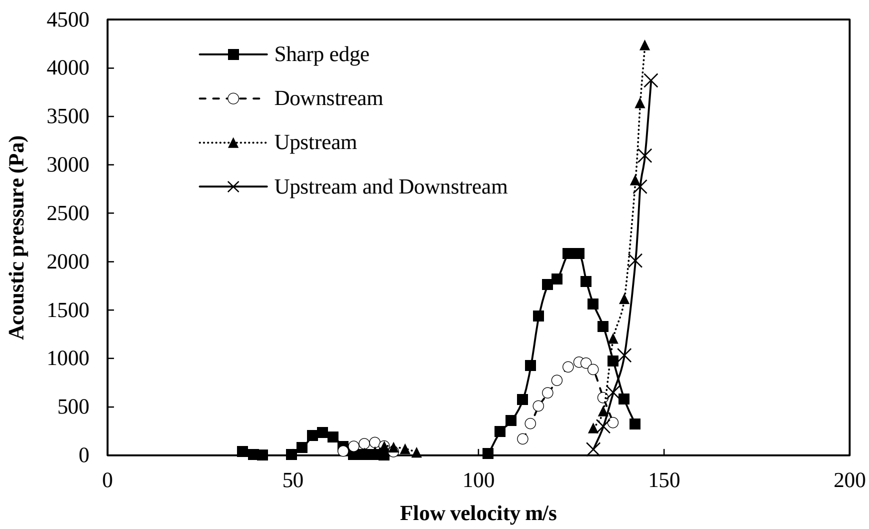

FIGURE 14: THE EFFECT OF ROUNDING THE UPSTREAM AND/OR THE DOWNSTREAM EDGE BY r = 25.4 mm.

Further geometries were investigated to address how the mass addition into the cavity can influence the acoustic resonance excitation. Three additional downstream edges were investigated; higher step, lower step, and a saw-tooth edge. Figure 15 shows the effect of these three configurations on the acoustic resonance excitation. It is observed that the acoustic pressure can be significantly reduced to values less than 1000 Pa when a saw-tooth edge is introduced. The higher step, which was expected to enhance the resonance excitation due to the increase in the mass addition into the cavity, results in suppressive performance and the resonance excitation is attenuated to values around 1150 Pa. The resonance excitation is also observed to be shifted to higher flow velocities when higher and lower steps are introduced.
Different spoilers were investigated at the downstream as well. The spoilers were able to deflect the flow at the downstream edge in different patterns. Straight spoilers were investigated in two different configurations; with the tip of the spoilers upstream and the tip of the spoilers downstream. Delta spoilers were also investigated with the converging angle in the direction of the flow. Moreover, the effect of placing a cylinder close to the downstream edge is investigated. Figure 16 shows a comparison between the base case, the straight spoilers, the delta spoilers, and the cylinder case. The cases investigated were observed to enhance the resonance excitation to values exceeding

3500 Pa in the case of the straight spoilers with the tip pointed downstream. The delta spoilers are observed to have no significant influence on the acoustic pressure values; however, the resonance is observed to be shifted to higher velocities.

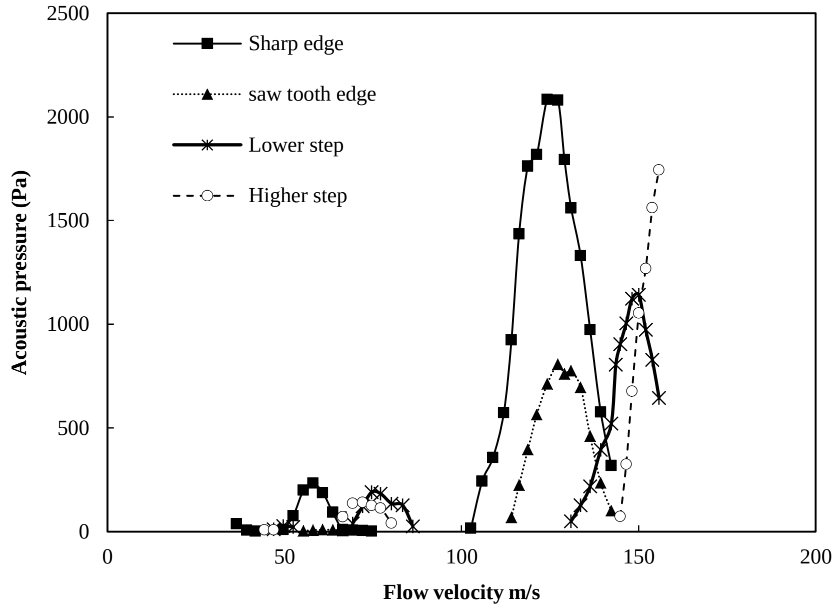

FIGURE 15: COMPARISON BETWEEN SHARP EDGE, SAW-TOOTH, AND STEP EDGES

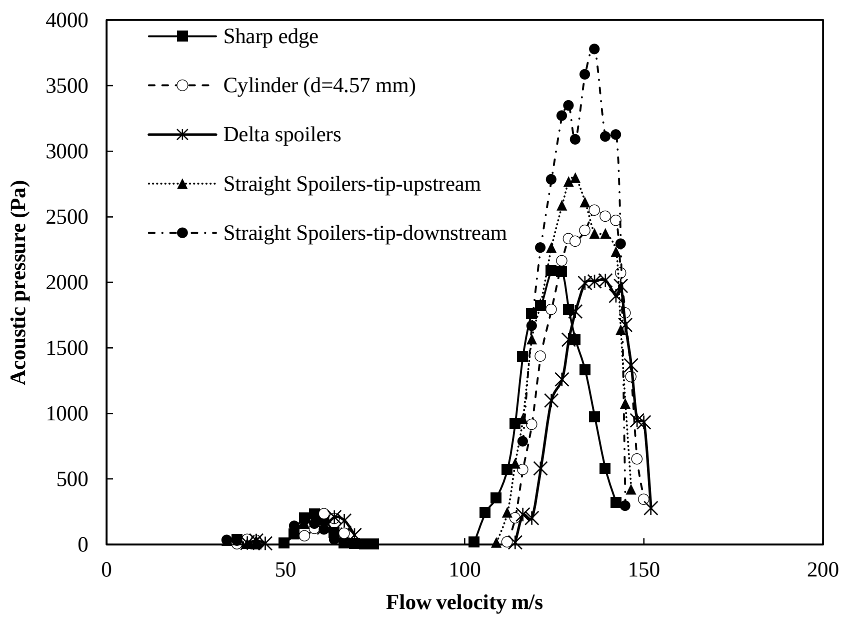

Figure 16: COMPARISON BETWEEN SHARP EDGE, DELTA SPOILERS, STRAIGHT SPOILERS, AND A CYLINDER

THE EFFECT ON STROUHAL NUMBER VALUES

The Strouhal number values were observed to be affected by two parameters; the edge geometry, and whether the edge is installed upstream or downstream of the cavity. To correlate the values for the cases investigated with the base case, an effective length is considered for each case. Table 1 summarizes the effect on Strouhal number values.

TABLE 1: EDGE EFFECT ON STROUHAL NUMBER

Edge geometry	Edge location	Effect on Strouhal number
Round edge	Upstream	change dependent on the radius
	Downstream	no significant effect
Chamfered edge	Upstream	change independent of the angle
	Downstream	change dependent on the angle
Lower step	Downstream	lower Strouhal number values
Saw tooth edge	Downstream	no significant effect

When a round or a chamfered edge is installed at the upstream edge, it is observed that Stouhal number values collapse with the base case values if an effective length is taken into consideration. The effective length of the cavity is (L+r) for the round edges and (L+l) for the chamfered edges, where r is the radius of the round edge and l is the length of the chamfered edge. For the lower step case, the effective length that can correlate the Strouhal number values is the cavity length combined with the thickness of the step. Using this effective length, which is 152.4 mm, results in Strouhal number values similar to that of the base case.

CONCLUSIONS

The effect of the downstream edge on the acoustic resonance excitation in rectangular cavities is investigated. The downstream edge geometry plays a significant role in the resonance excitation mechanism and the modification of this geometry can attenuate the effects of the resonance excitation considerably. However, the modifications cannot completely suppress the resonance excitation as the downstream edge only influence the flow impingement while the shear layer is initiated at the upstream edge. Chamfering the downstream edge can reduce the acoustic pressure to values less than 600 Pa compared to the base case with 2000 Pa. It is also observed that chamfering the downstream edge results in shifting the resonance to higher velocities, hence changing the Strouhal number values. For chamfered edges, the change in the Strouhal number can be adjusted by using an effective length that depends on the angle of the chamfered edge. Contrary to the chamfered edges, rounding the downstream edges has no significant influence on the Strouhal number values. However, the acoustic pressure is observed to be also reduced to values less than 1000 Pa. A higher step at the downstream edge, which is known to increase the flow into the cavity, results in attenuating the acoustic resonance with a slight shift in the resonance excitation to higher flow velocities; moreover, using a lower step increases the shift in the acoustic resonance with almost same values of acoustic pressure compared to the higher step case.

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