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Effect of impingement edge geometry on the acoustic resonance excitation and Strouhal numbers in a ducted shallow cavity

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Abstract. Flow-excited acoustic resonance in ducted cavities can produce high levels of acoustic pressure that may lead to severe damage. This occurs when the flow instability over the cavity mouth, which is created by the free shear layer separation at the upstream edge, is coupled with one of the acoustic modes in the accommodating enclosure. Acoustic resonance can cause high amplitude fluctuating acoustic loads in and near the cavity. Such acoustic loads could cause damage in sensitive applications such as aircraft weapon bays. Therefore, the suppression and mitigation of these resonances are very important. Much of the work done in the past focused on the fluid-dynamic oscillation mechanism or suppressing the resonance by altering the edge condition at the shear layer separation. However, the effect of the downstream edge has received much less attention. This paper considers the effect of the impingement edge geometry on the acoustic resonance excitation and Strouhal number values of the flow instabilities in a ducted shallow cavity with an aspect ratio of 1.0. Several edges, including chamfered edges with different angles and round edges with different radii, were investigated. In addition, some downstream edges that have never been studied before, such as saw-tooth edges, spanwise cylinders, higher and lower steps, and straight and delta spoilers, are investigated. The experiments are conducted in an open-loop wind tunnel that can generate flows with a Mach number up to 0.45. The study shows that when some edge geometries, such as lower steps, chamfered, round, and saw-tooth edges, are installed downstream, they demonstrate a promising reduction in the acoustic resonance. On the other hand, higher steps and straight spoilers resulted in intensifying the acoustic resonance. In addition, the effect of edge geometry on the Strouhal number is presented.

Keywords: acoustic resonance; flow impingement; rectangular cavity; downstream edge; strouhal number

1. Introduction

Flow over cavities is a design concern in many engineering applications, such as aircraft weapon bays (Rossiter 1962, Rossiter and Kurn 1962, Lawson and Barakos 2011), side branches in piping systems (Brugeman *et al*. 1991, Knotts and Selamet 2003, Lafon *et al*. 2003), and control valves (Ziada *et al*. 1989, Lacombe and Lafon 2013). Although the geometry of such

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configurations are relatively simple, the resulting fluid dynamic is much more complicated. When flow passes over a cavity, a boundary layer separation at the cavity's upstream edge occurs and results in the formation of a shear layer over the cavity's mouth. The shear layer formation creates vortices that are carried with the flow to impinge onto the downstream edge of the cavity. The impingement of these vortices on the downstream edge generates pressure perturbations that travel back upstream to enhance the shear layer separation and close a feedback cycle of oscillation. Rockwell (1983) classified the self-sustained oscillations of the flow over the cavity into three types: fluid-resonant, fluid-dynamic, and fluid-elastic oscillations. The fluid-resonant oscillations, which are the case in ducted cavities, occur when the shear layer oscillations over the cavity mouth are coupled with one of the acoustic modes of the duct housing the cavity, as illustrated in Fig. 1. The sound wave coupling with the flow oscillations creates a phenomenon known as the flow-excited acoustic resonance (Rockwell and Naudascher 1978, Rockwell *et al*. 2003, Mohany and Ziada 2005, Mohany 2007, Gloerfelt 2009, Mohany and Ziada 2011, Mohany *et al*. 2014, Shaaban and Mohany 2015). This phenomenon can result in high levels of acoustic pressure that may lead to catastrophic damage to the equipment. As shown schematically in Fig. 2, flow-excited acoustic resonance in ducted cavities may occur if the frequency of the shear layer mode (m) coincides with the frequency of an acoustic mode (n) in the accommodating enclosure, and the flow has enough energy to overcome the acoustic damping of the system. When flow-excited acoustic resonance is generated, a lock-in region is observed, where the shear layer oscillation frequency locks into one of the acoustic resonance frequencies of the confined enclosure over a certain range of flow velocity. Within this lock-in region a sudden increase in the acoustic pressure occurs. The number of vortices developed by the shear layer in the cavity represents the hydrodynamic mode of the shear layer, which is governed by the Strouhal relationship. Despite the fact that fluid-dynamic oscillations of flow over cavities have received significant attention in the literature since the 1950s, the fluid-resonant feedback mechanism in ducted cavities has received less attention.

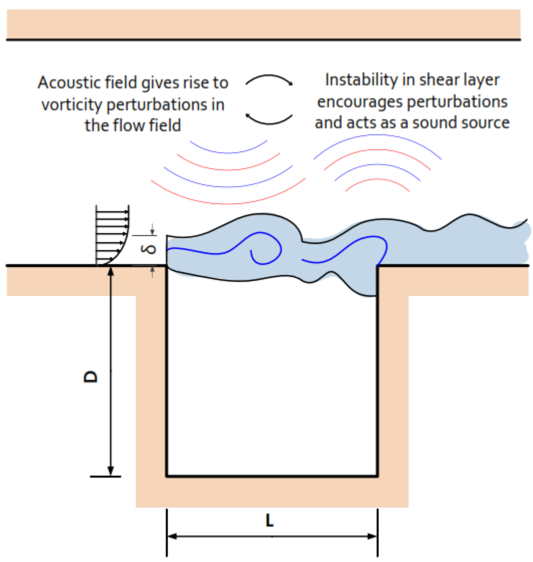


Fig. 1 Fluid-resonant feedback mechanism of the cavity flow oscillations (Shaaban and Mohany 2015)

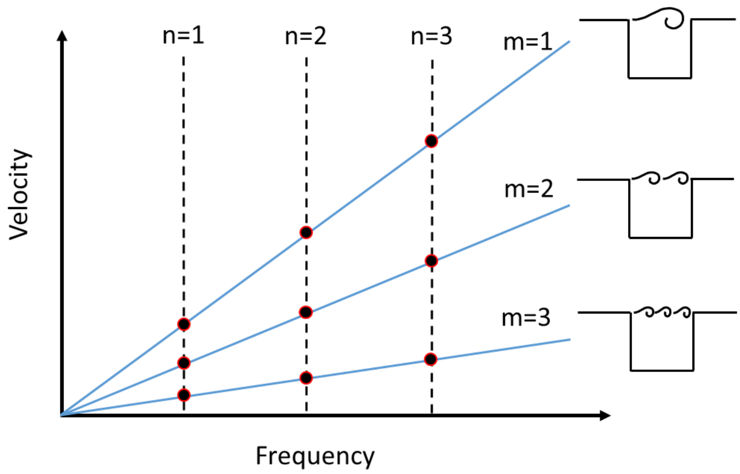


Fig. 2 Schematic of the shear layer modes (m) and their coincidence with the acoustic cross-modes (n) of the duct housing the cavity

Self-sustained flow oscillations in cavities can be suppressed by using passive methods, such as modifying the cavity geometry (Baldwin and Simmons 1986, Bruggeman *et al*. 1991, Knotts and Selamet 2003), placing a control cylinder near the upstream edge to generate high frequency vortices that can disrupt the cavity shear layer oscillations (Keirsbulck *et al*. 2008, Illy *et al*. 2008, Omer and Mohany 2014), adding spoilers at the upstream edge that can generate orthogonal vortices to the cavity shear layer (Bolduc *et al*. 2013, Omer *et al*. 2014), and placing upstream mounted blocks with flow reattachment close to the cavity's leading edge (Shaaban and Mohany 2015). One of the methods, which is the subject matter of this work, is the effect of the downstream edge geometry on the acoustic resonance excitation in ducted cavities. The geometry of the downstream edge controls the flow impingement, which in turn influences the feedback cycle of the oscillation. Moreover, changing the geometry of the downstream cavity's edge will have an effect on the mass addition (or removal) in the cavity. As suggested by Heller and Bliss (1975), the mass addition and removal process creates a pressure wave that travels upstream, and it can be modelled by a piston movement installed at the downstream edge of the cavity. Therefore, modifying the downstream edge geometry to alter the mass exchange process can be used to mitigate the shear layer oscillations in the cavity. Heller and Bliss (1975) investigated a chamfered downstream edge combined with/without a spoiler located at the upstream edge. The chamfered edge was found to be effective in suppressing the self-sustained flow oscillations; however, the effect of the chamfered angle on the acoustic resonance excitation and Strouhal number values was not considered in their work. Zhang *et al*. (1998) computationally investigated the effect of the downstream edge geometry on the cavity shear layer oscillations for a supersonic flow. Only round and chamfered edges were investigated. They found that these geometries were able to reduce the pressure oscillations in the cavity. However, their study was only concerned with the fluid-dynamic type of oscillations, and the fluid-resonant oscillations that result in flow-excited acoustic resonance were not investigated. Recently, Vikramaditya and Kurian (2014) studied the effect of the downstream edge geometry on the cavity oscillations in supersonic flow. Only chamfered edges were investigated, including chamfering the entire depth of the cavity, which was found to be effective in mitigating the pressure perturbations in the cavity. However, their experiments were performed at a specific flow velocity (Mach number of 1.63) and the effect of the edges' geometry on Strouhal number values was not investigated.

Despite the fact that flow over cavities has received considerable attention in the literature, there are still some issues that need to be clarified, especially those related to the fluid-resonant feedback mechanism in cavities. Most of the previous work in the literature was focused on the fluid-dynamic oscillation mechanism in cavities, and the effect of a *few* edge geometries on the flow oscillations. However, it is not clear whether altering the flow impingement of the shear layer in the cavity can be used effectively to disrupt the fluid-resonant feedback mechanism and thereby control the flow-excited acoustic resonance phenomenon in ducted cavities. Moreover, most of the studies performed earlier investigated the shear layer oscillations in cavities at a specific flow velocity, which does not show how the phenomenon develops within the lock-in region. Finally, the effect of the geometry of the upstream and/or the downstream edge on the acoustic resonance excitation and Strouhal number values was not compared and investigated under the same conditions before. Therefore, this paper provides a quantitative comparison of the impingement edge effect on the shear layer instability and the excited acoustic resonance. In addition, several geometries of the downstream cavity edges, including geometries that were not investigated in the literature before, such as saw-tooth edge, higher and lower steps, delta and straight spoilers, and a cylinder installed at the downstream edge, are investigated to address the influence of the edge geometry on the resonance excitation and the Strouhal number values. Moreover, for the chamfered and round edges the results are compared with cases where the edges are installed either at the upstream edge or at both the upstream and downstream edges of the cavity to provide a better understanding of their effect on acoustic resonance excitation.

2. Experimental setup

The experiments were conducted in an open-loop wind tunnel. The setup consists of a rectangular duct that has a height of 254 mm and a width of 127 mm. The duct is made of 25.4 mm thick acrylic sheets, as shown in Fig. 3. 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. 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%. This wide range of velocities covers many practical applications such as side branches in piping systems, gate valves in ducts, and aircraft weapon bays. 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 normalized pressure distribution of the first acoustic cross-mode in the duct housing the cavity is shown in Fig. 4. The experiments were repeated for some cases several times to ensure 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 were 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 with a diameter of 4.57 mm attached close to the downstream edge. The dimensions and configurations of the edges are illustrated in Figs. 5 and 6 and summarized in Table 1.

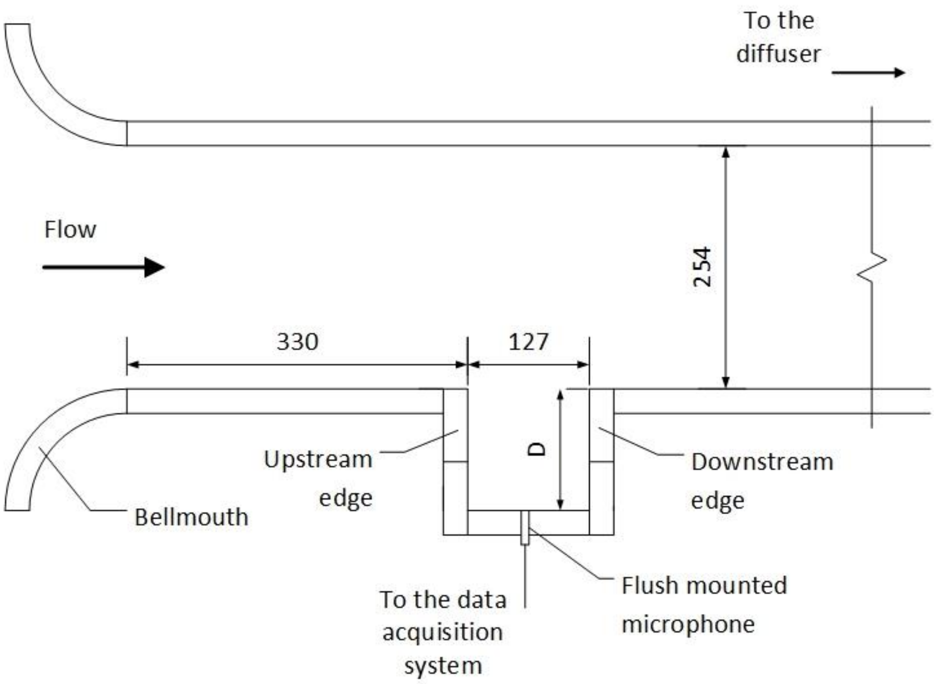


Fig. 3 Schematic drawing of the test section (all dimensions are in mm)

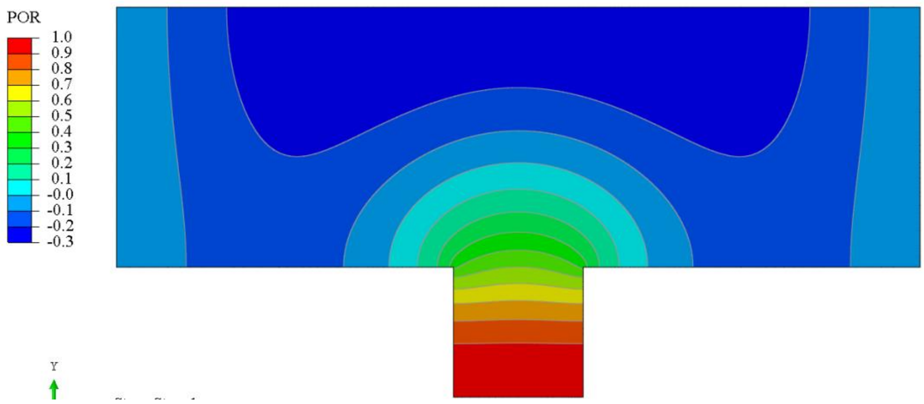


Fig. 4 Distribution of the normalized pressure for the first acoustic cross-mode

Table 1 Geometries of the different edges used in this work

Edge geometry	**Description**
Rectangular edge	Base case – Fig. 5(a)
Round edge	Radius: 25.4 mm and 12.7 mm. Fig. 5(b)
Chamfered edge	Angle: 107, 120, 135, 150. Fig. 5(c)
Saw-tooth edge	Fig. 5 (i)
Straight spoilers	Height =8.2 mm, Fig. 6(b)
Delta spoilers	Height =16 mm, Fig. 6(a)
Higher/Lower steps	19.05 mm/25.4 mm, Figs. 5(d) and (f)
Cylinder	Diameter = 4.57 mm, Fig. 5(h)

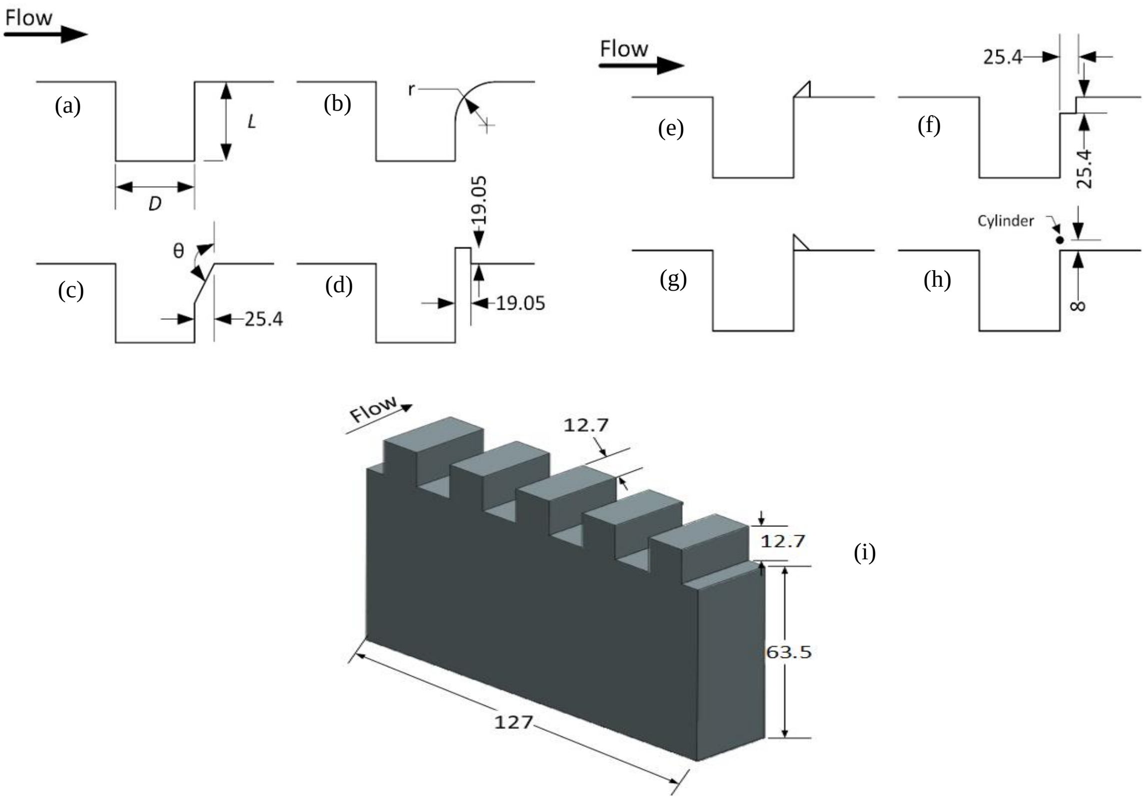
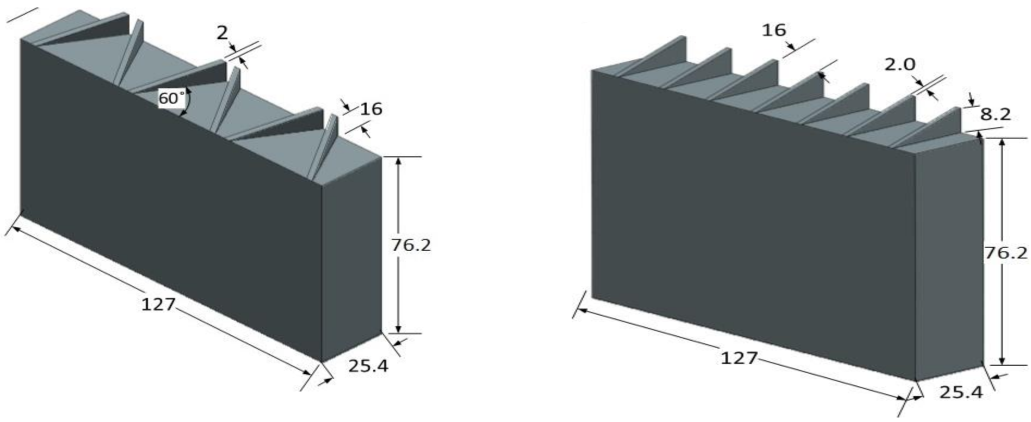


Fig. 5 Base cavity case with (a) sharp edges, (b) round edges, (c) chamfered edges, (d) higher step, (e) spoilers tip downstream, (f) lower step edge, (g) spoilers tip upstream, (h) cylinder at the downstream edge, (i) saw-tooth edge. (all dimensions are in mm)



(a) Delta spoiler (b) Straight spoiler

Fig. 6 3D drawing of the delta and straight spoiler edges (all dimensions are in mm)

3. Results

In this section the results are presented and discussed. The effect of the tested configurations at the downstream edge of the cavity on the acoustic resonance excitation is compared to that of the base cavity case, with sharp edges installed both upstream and downstream. The base cavity case is observed to excite the three shear layer modes as illustrated in the waterfall plot in Fig. 7. Each line in this waterfall plot represents a pressure spectrum measured at a specific flow velocity starting from 0 to 140 m/s. The three shear layer modes excite the first acoustic cross-mode of the duct housing the cavity. This occurs as the frequency of the shear layer mode approaches the frequency of the acoustic cross-mode. 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 Fig. 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.

3.1 Effect of chamfered edges

Several chamfered edges are investigated in different configurations. Fig. 9 shows the acoustic pressure when 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 that of 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 decay as the angle of the chamfered edge increases. This occurs until an angle of 135˚, and then 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.

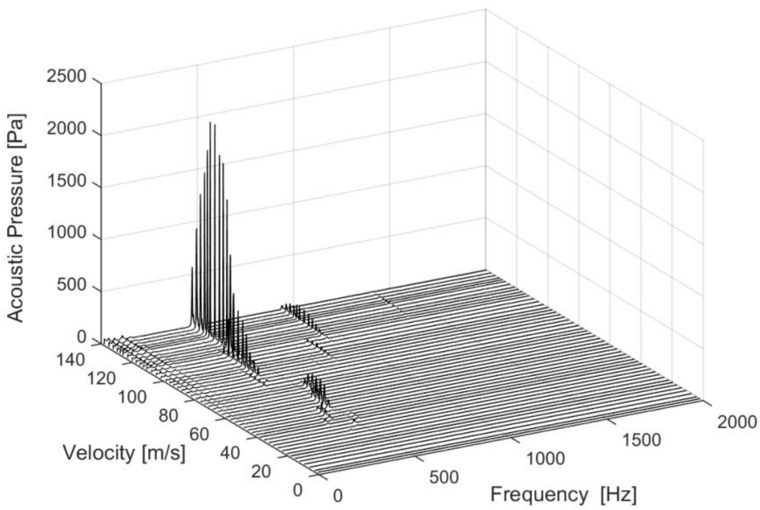


Fig. 7 3D waterfall plot for the base cavity case with sharp edges

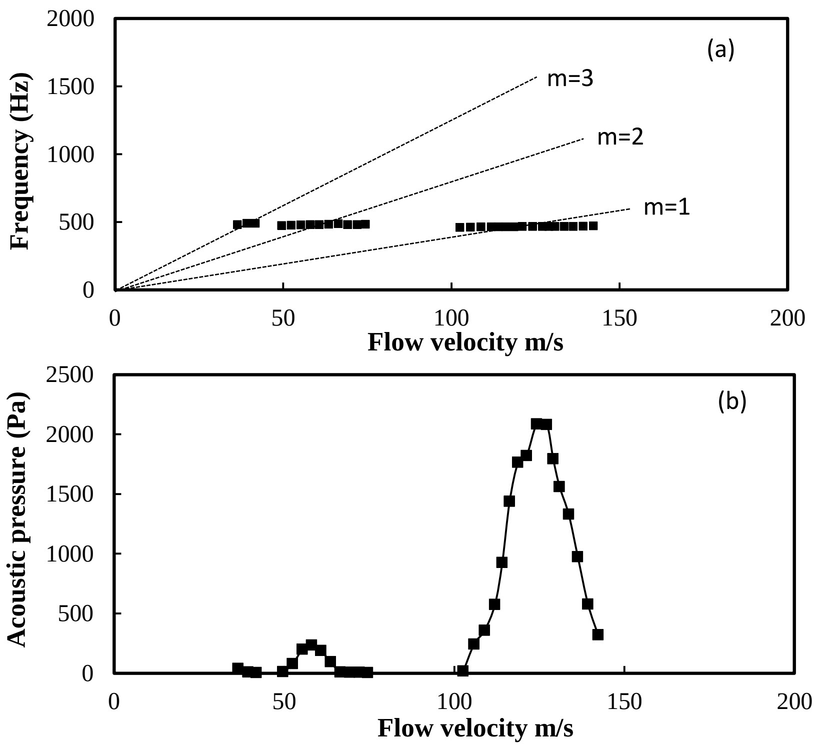


Fig. 8 Aeroacoustic response of the first acoustic cross-mode in the base cavity case with sharp edges (a) frequency of the dominant oscillations, and (b) pressure of the excited acoustic resonance

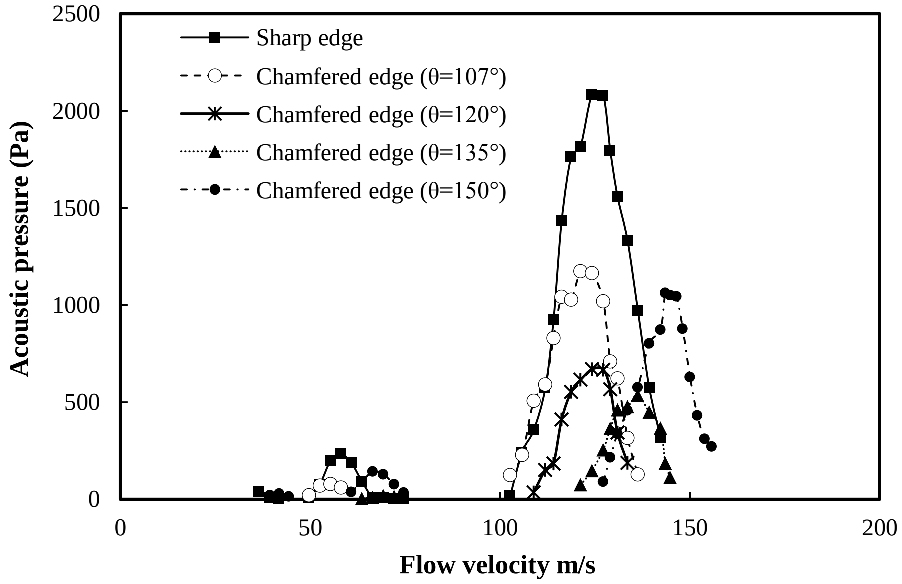


Fig. 9 The aeroacoustic response of a rectangular cavity with different chamfered edges installed at the downstream edge compared with the base cavity case

This shift is observed to be dependent on the angle of the chamfered edge as well. As the frequency of the acoustic cross-mode remains constant, the Strouhal number values seem to vary for each case due to the shift in the resonance excitation. However, considering an effective cavity length that includes the thickness of the chamfered edge, i.e. the projected length of the chamfered edge in the flow direction, results in a normalized value of the Strouhal number, as shown in Fig. 10. This works when the chamfered angle is equal to or greater than 135°. However, for chamfered angles less than 135°, the effective cavity length is the same as the length of the base cavity case with sharp edges.

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 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 of oscillation. To compare the effect of chamfering the upstream and/or the downstream edge of the cavity, Fig. 11 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 for chamfered edges with angles of 135˚ and 150˚, as shown in Fig. 12. It can be concluded from these figures that the shift in the acoustic resonance excitation is significantly influenced by which edge is chamfered. For upstream chamfered edges, the effective cavity length should include the thickness of the chamfered edge regardless of its angle. When chamfering both upstream and downstream edges a further shift in the resonance excitation occurs as the effective cavity length increases compared to either case alone. The aeroacoustic response of the cavity when both upstream and downstream edges are chamfered is shown in Fig. 13 as a function of the Strouhal number normalized by the effective cavity length.

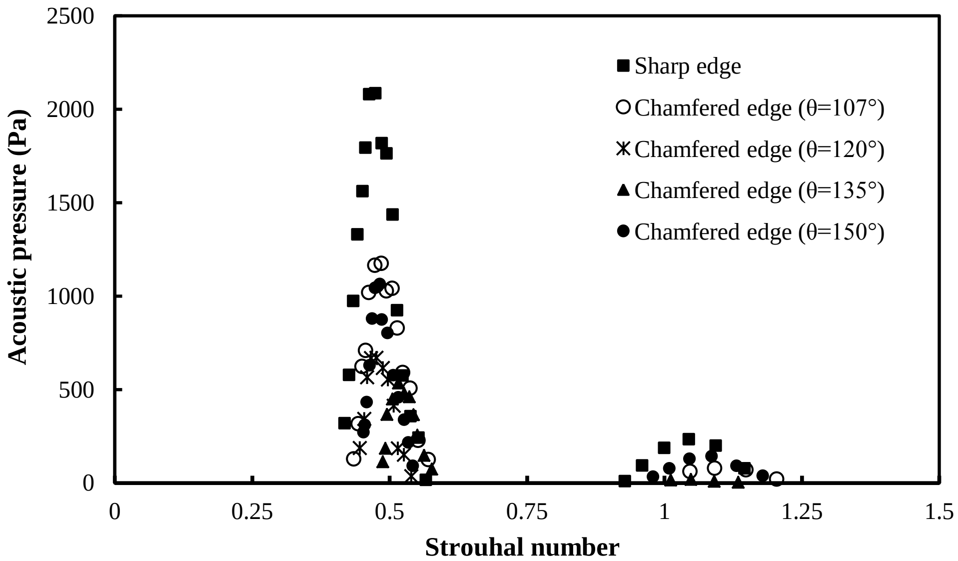


Fig. 10 Strouhal numbers of the cavity shear layer using the effective length for sharp and chamfered edges at the downstream edge

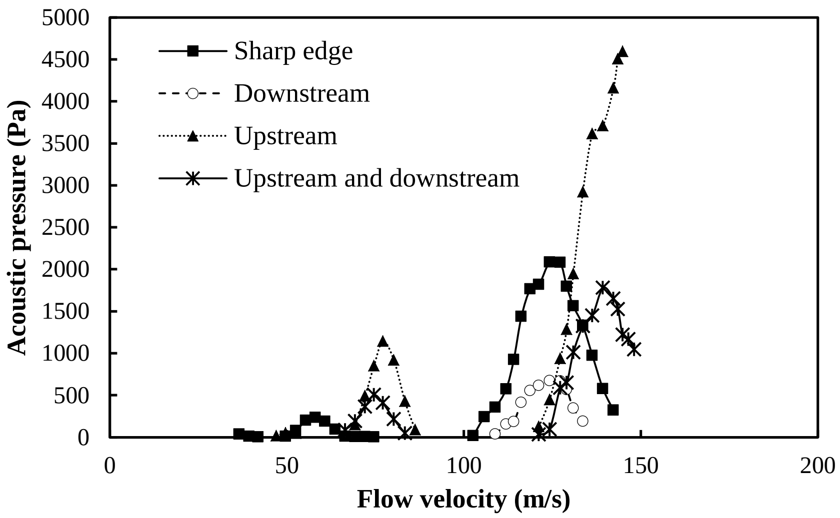
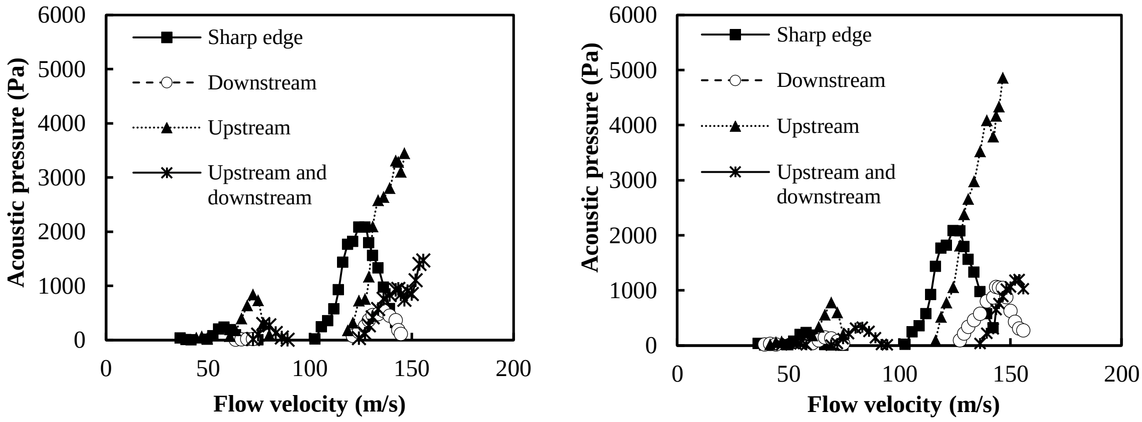


Fig. 11 The effect of chamfering the upstream and/or the downstream edge by 120°



(a) Chamfered angle is 135° (b) Chamfered angle is 150°

Fig. 12 The effect of chamfering the upstream and/or the downstream edge

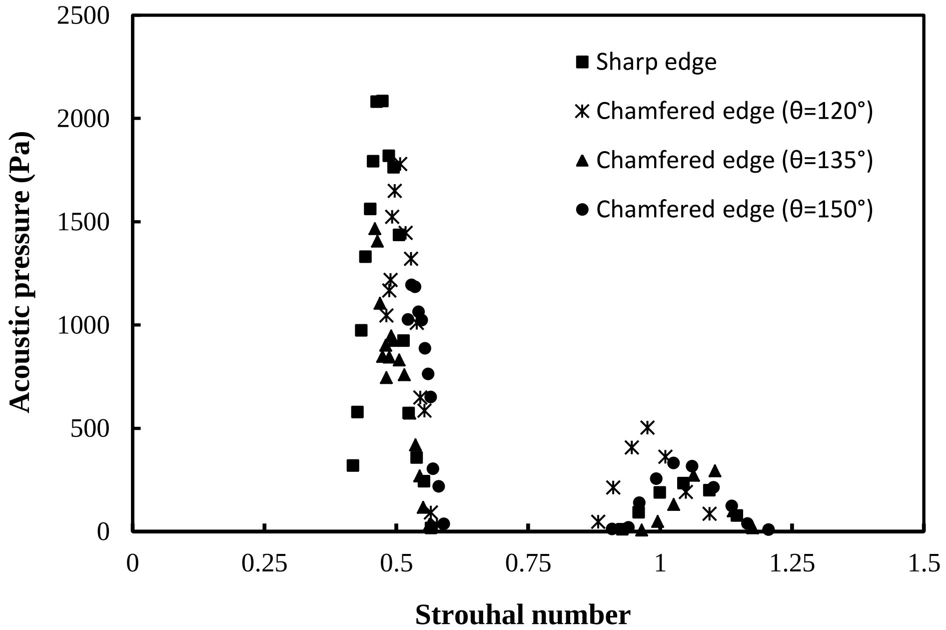
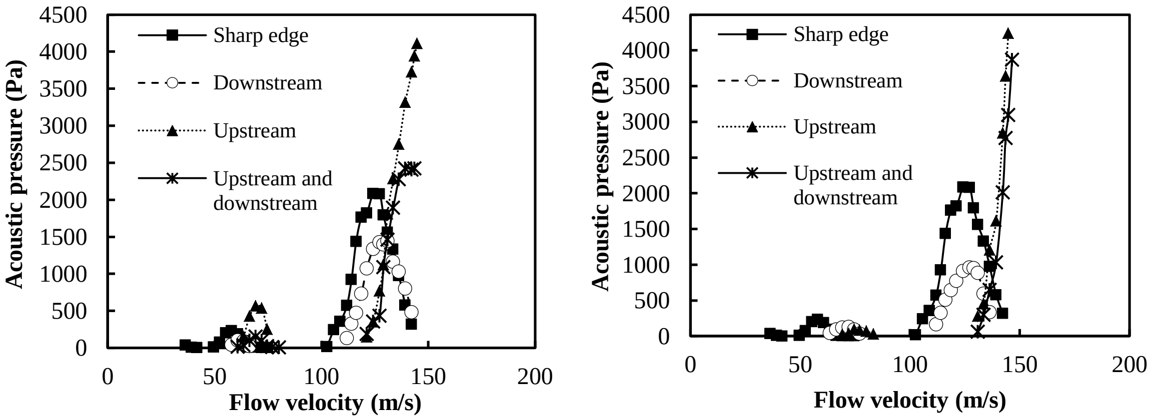


Fig. 13 Strouhal numbers of the cavity shear layer using the effective length for sharp and chamfered edges at both the upstream and downstream edge

3.2 Effect of round edges

To further investigate the edge geometry effect on the acoustic resonance excitation, round edges with two different radii were tested. Fig. 14(a) shows the effect of rounding the edges to a 12.7 mm radius. Similar to that for chamfered, the acoustic pressure is reduced when only the downstream edge is rounded. Interestingly, rounding the downstream edge has no significant effect on shifting the acoustic resonance excitation to higher velocities. Therefore, the effective cavity length for this case is the same as that of the base cavity with sharp edges. However, rounding the upstream edge results in an acoustic pressure that is much higher than that of the base case, and a shift in the acoustic resonance excitation corresponding to an increase in the cavity length with the radius of the round edge is observed. Moreover, rounding both upstream and downstream edges has no significant difference on Strouhal number values from the case where only the upstream edge is rounded. However, the acoustic pressure for this case falls between the corresponding values where only the upstream or the downstream edge is rounded. This indicates that the impingement of the shear layer vortices on the downstream edge generates an acoustic source with a different phase than that generated at the upstream edge. The net effect of both sources is what controls the amplitude of the excited acoustic resonance. 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 Fig. 14(b). In general, increasing the radius of the upstream rounded edge results in a greater 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 excitation. The aeroacoustic response of the cavity, when the upstream and/or the downstream edges are rounded, is shown in Fig. 15 as a function of the Strouhal number normalized by the effective cavity length.



(a) Round edge radius is 12.7 mm　　(b) Round edge radius is 25.4 mm

Fig. 14 Effect of rounding the upstream and/or the downstream edge on the acoustic resonance excitation

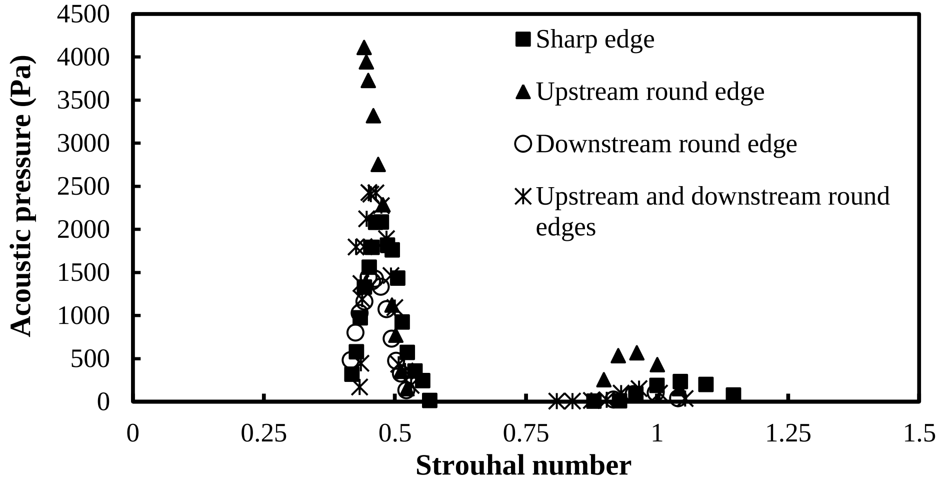


Fig. 15 Strouhal numbers of the cavity shear layer using the effective length for sharp and round edges at the upstream and/or the downstream edge

3.3 Higher and lower steps

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. Fig. 16 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 at the downstream edge. The lower step, which was expected to enhance the resonance excitation due to an increase in the mass addition into the cavity, resulted in a suppressive performance instead, and the resonance excitation was attenuated to values around 1150 Pa. It was the higher step that enhanced the acoustic resonance excitation; however the velocity required to complete the experiments was beyond the maximum flow velocity achievable by the blower. The resonance excitation is also observed to be shifted to higher flow velocities when the lower and higher steps are introduced. The aeroacoustic response of the cavity with these downstream edges is shown in Fig. 17 as a function of the Strouhal number normalized by the effective cavity length. For the saw-tooth edge the effective cavity length is found to be the same as that of the base case with sharp edges. However, for the lower and higher steps the effective cavity length should include either the step length in the flow direction or the step height perpendicular to the flow, respectively.

3.4 Spoilers and downstream cylinder

Different spoilers were investigated at the downstream edge 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 flow direction. Moreover, the effect of placing a cylinder close to the downstream edge is investigated.

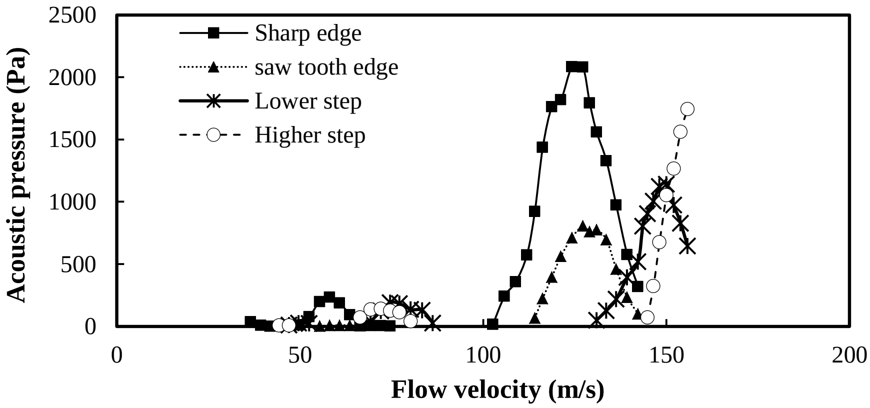


Fig. 16 The aeroacoustic response of a rectangular cavity with saw-tooth edge, lower step, and higher step installed at the downstream edge compared with the base cavity case

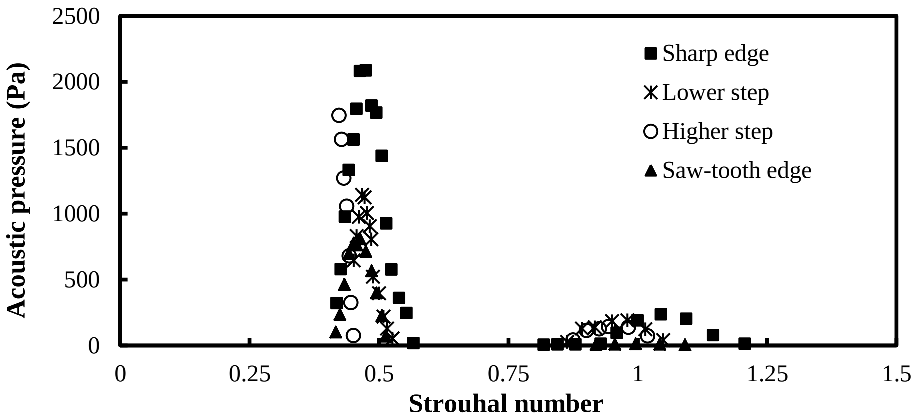


Fig. 17 Strouhal numbers of the cavity shear layer using the effective length for saw-tooth edge, lower and higher steps compared with the base cavity case

Fig. 18 shows a comparison between the base case, the straight spoilers, the delta spoilers, and the cylinder case. The straight spoilers with the tip pointed downstream were observed to intensify the resonance excitation with the acoustic pressure exceeding 3500 Pa compared to about 2000 Pa for the base cavity case with sharp edges. This is due to the fact that this spoiler enhances the mass addition into the cavity, which strengthens the flow-acoustic coupling and results in higher values of acoustic pressure compared to that of the base cavity case. The downstream delta spoilers are observed to have no significant influence on the acoustic resonance excitation.

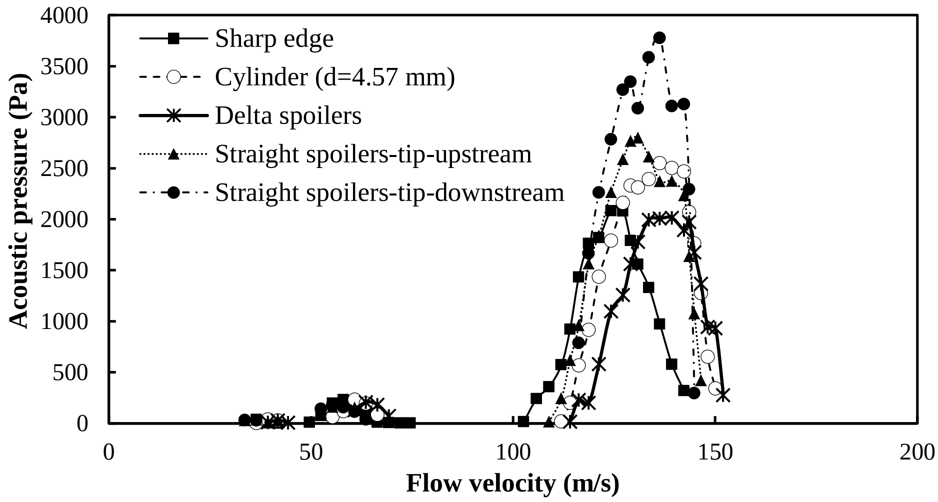


Fig. 18 The aeroacoustic response of a rectangular cavity with delta and straight spoilers, and a cylinder installed at the downstream edge compared with the base cavity case

Table 2 Edge effect on Strouhal number

Edge geometry	Edge location	Effect on Strouhal number	Effective length
Round edge	Upstream	change dependent on the radius	$L_{eff} = L + r$ where L is the base cavity length and r is the radius of the edge
	Downstream	no significant effect	$L_{eff} = L$
Chamfered edge	Upstream	change independent of the angle	$L_{eff} = L + t$ where t is the projected chamfered length in the flow direction
	Downstream	change dependent on the angle	$L_{eff} = L$, if chamfered angle is less than 45° $L_{eff} = L + t$, if chamfered angle is greater than or equal to 45°
Lower step	Downstream	change dependent on the step length	$L_{eff} = L + l$ where l is the step length in the flow direction
Higher step	Downstream	change dependent on the step height	$L_{eff} = L + h$ where h is the step height perpendicular to the flow direction
Saw tooth edge	Downstream	no significant effect	$L_{eff} = L$

4. 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 2 summarizes the effective length that should be considered for the different cavity edges that are considered in this work.

5. Conclusions

The effect of the downstream edge geometry on the acoustic resonance excitation in rectangular ducted 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 influences 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 also observed to be reduced to values less than 1000 Pa. A lower step at the downstream edge results in attenuating the acoustic resonance with a slight shift in the resonance excitation to higher flow velocities; moreover, using a higher step increases the shift in the acoustic resonance with almost the same values of acoustic pressure compared to the lower step case. The straight spoilers were observed to intensify the resonance excitation with an acoustic pressure exceeding 3500 Pa for the case of the straight spoilers with the tip pointed downstream. This is due to the fact that the straight spoilers seem to enhance the mass addition into the cavity which strengthens the flow-acoustic coupling and results in higher values of acoustic pressure compared to that of the base cavity case.

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