Passive Control of Trapped Mode Resonance of Ducted Cavities

M. Bolduc
Department of Mechanical Engineering,
McMaster University,
Hamilton, ON L8S4L7, Canada

M. Elsayed
Department of Mechanical Engineering,
McMaster University,
Hamilton, ON L8S4L7, Canada

S. Ziada
Department of Mechanical Engineering,
McMaster University,
Hamilton, ON L8S4L7, Canada

Gas flow over ducted cavities can excite strong acoustic resonances within the confined volumes housing the cavities. When the wavelength of the resonant acoustic modes is comparable with, or smaller than, the cavity dimensions, these modes are referred to as trapped acoustic modes. The flow excitation mechanism causing the resonance of these trapped modes in axisymmetric shallow cavities has been investigated experimentally in a series of papers by Aly and Ziada (2010, "Flow-Excited Resonance of Trapped Modes of Ducted Shallow Cavities," J. Fluids Struct., ***26****, pp. 92–120; 2011, "Azimuthal Behaviour of Flow-Excited Diametral Modes of Internal Shallow Cavities," J. Sound Vib.,* ***330****, pp. 3666–3683; 2012, "Effect of Mean Flow on the Trapped Modes of Internal Cavities," J. Fluids Struct.,* ***33****, pp. 70–84). In this paper, the same experimental set-up is used to investigate the effect of the upstream edge geometry on the acoustic resonance of trapped modes. The investigated geometries include sharp and rounded cavity corners, chamfering the upstream edge, and spoilers of different types and sizes. Rounding-off the cavity edges is found to increase the pulsation amplitude substantially, but the resonance lock-on range is delayed, i.e., it is shifted to higher flow velocities. Similarly, chamfering the upstream corner delays the onset of resonance, but maintains its intensity in comparison with that of sharp edges. Spoilers, or vortex generators, added at the upstream edge have been found to be the most effective means to suppress the resonance. However, the minimum spoiler size which is needed to suppress the resonance increases as the cavity size becomes larger.* [DOI: 10.1115/1.4027377]

Keywords: shallow cavity, diametral modes, trapped modes, acoustic resonance, suppression of acoustic resonance

1 Introduction

Flow-excited acoustic resonances within cavities have been reported for many engineering applications, including piping systems, control valves, jet engines, and nuclear reactors [1–7]. Acoustic resonances can cause acute noise levels and/or acoustic fatigue failures [7,8]. The excitation mechanism consists of two main phenomena; namely, the instability of the cavity shear layer and an upstream feedback effect. At the upstream edge, the sound field introduces velocity perturbations, which grow rapidly as they are convected with the shear layer to form vortex-like structures. As these vortices reach the downstream corner of the cavity, a portion of their energy is converted into acoustic energy due to their interaction with the acoustic particle velocity field of the resonant mode [9]. This generated acoustic energy sustains the resonance, and completes the feedback loop. Rockwell and Naudascher [10] classified this mechanism as fluid-resonant because the upstream feedback is provided by the resonant sound field.

This paper focuses on several passive means to suppress the acoustic resonance of the diametral modes of an axisymmetric cavity in a duct. These diametral modes can be classified as (nearly) trapped acoustic modes, which are known to occur in wave guides where the perturbation energy is localized in regions containing some changes in the domain geometry or the fluid properties [11]. For the case under investigation, the presence of the axisymmetric cavity in the duct lowers the local spinning mode cut-off frequency below the cut-off frequency of the main duct. This reduction in frequency results in hindering local acoustic energy generated at the cavity cut-off frequency from propagating away from the cavity along the duct [12] and thereby a new resonance mode at this frequency is introduced to the system. Hein and Koch [13] predicted numerically the existence of diametral modes of infinitely long cavity-duct configurations for no-flow condition. Aly and Ziada [1–3] reported strong flow excitation of the diametral modes of shallow cavities for a range of cavity length comparable with the main pipe diameter. The self-excitation mechanism of longitudinal and diametral acoustic modes is very much the same except that the longitudinal modes near the cavity are basically two-dimensional, whereas the trapped diametral modes are three-dimensional. Therefore, the main difference between the two resonance mechanisms is that the longitudinal modes trigger the free shear layer uniformly over the circumference at the same time instant, whereas the interaction of the shear layer with diametral modes is much more complex because the amplitude and phase of the acoustic particle velocity are not uniform over the cavity circumference.

Control methods for cavity oscillations have been categorized as either active or passive. Active means involve inputting external energy [14], while passive control methods involve modifications of the geometry of the cavity. This paper describes passive control methods carried out to suppress the acoustic resonance of an internal axisymmetric cavity. These methods include the addition of spoilers, chamfers, and rounding at the leading edge of the cavity. Such modifications have been shown to be effective, to varying degrees, in past studies of longitudinal resonances in which the acoustic wavelength was much longer than the cavity dimension [15,16]. In the present case of trapped diametral modes, the acoustic wavelength is shorter than the cavity diameter and therefore the acoustic field exciting the cavity shear layer is three-dimensional.

2 Experimental Setup

2.1 Test Facility. This study was performed using an open loop wind tunnel with a centrifugal 50 hp air blower. The test

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Contributed by the Pressure Vessel and Piping Division of ASME for publication in the Journal of Pressure Vessel Technology. Manuscript received August 25, 2013; final manuscript received April 5, 2014; published online August 19, 2014. Assoc. Editor: Jong Chull Jo.

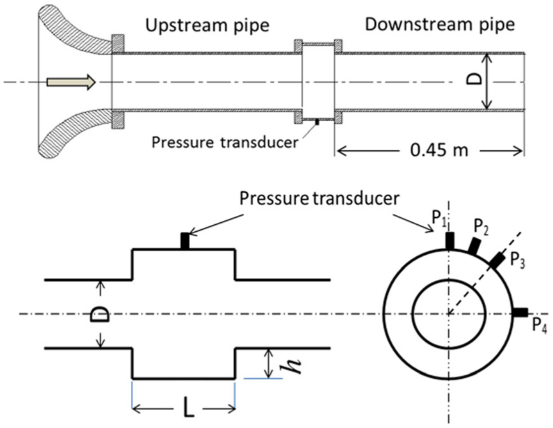

Fig. 1 Geometry of the test section and parameters of the axisymmetric cavity together with the locations of pressure transducers

section was made of acrylic pipes attached to flanges to accommodate the axisymmetric cavity [1]. The inner diameter of the main pipe was $D = 153$ mm. Figure 1 shows schematics of the test section geometry, including the main parameters of the cavity.

O-rings were used between the flanges to ensure that the test section was properly sealed. At the middle of the cavity floor, four pressure transducers (P1–P4) were flush mounted around the circumference at angles of 0, 22.5, 45, and 90 deg to capture the maximum acoustic pressure. A similar arrangement used in Ref. [2] showed that all modes are spinning except the lowest one which was partially spinning. Therefore, the pressure transducer showing the maximum pressure pulsation amplitude was used to measure the resonance intensity. This approach, rather than constructing the cavity pressure field for each measurement, seems adequate, given the nature of the excited modes and the fact that the results are used only for comparison purposes between cavities of similar geometry.

The cavity length and depth were varied by means of adding or removing various flanges with different diameters and thicknesses, but the pressure transducers were always retained at the cavity middle. Therefore it was possible to investigate the effects of the suppression devices on different cavity sizes. As illustrated in Table 1, six cavities were used in the present experiments. These included three cavity depths, $h/D = (1/12)$, $(2/12)$, and $(4/12)$, and two cavity lengths for each depth ($1''$ and $2''$). The base cases (B1–B6), or the cavities with sharp edges and no suppression devices, were tested first to generate reference data before proceeding with testing the suppression devices.

The need to test the effect of various suppression devices on different cavity sizes can be elucidated with the aid of Fig. 2, which shows numerical simulation results of the first diametral mode for three axisymmetric cavities with the same length (25.4 mm), but different depths [1]. As the cavity becomes deeper, the acoustic pressure axial distribution for the first mode decays faster and less acoustic energy is transmitted into the main duct. Therefore, acoustic resonances of deeper cavities can be stronger than those of shallower cavities under similar flow conditions. Consequently, some devices which suppress the resonance for shallow cavities may be ineffective in suppressing the more robust resonance of deeper cavities. For this reason, the effectiveness of the suppressing devices developed in this paper is tested on cavities with three different depths for each length.

Table 1 Dimensions of tested cavities

Cavity size	h (mm/in.)	h/D	L/h
B1	(12.7/0.5)	1/12	2
B2	(12.7/0.5)	1/12	4
B3	(25.4/1.0)	2/12	1
B4	(25.4/1.0)	2/12	2
B5	(50.8/2.0)	4/12	0.5
B6	(50.8/2.0)	4/12	1

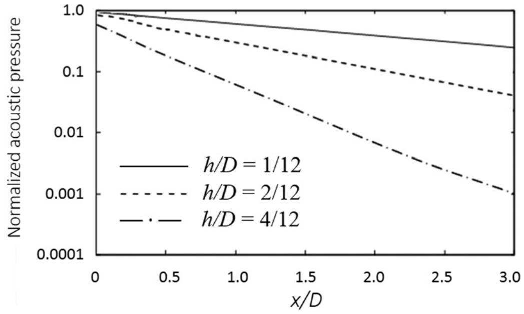

Fig. 2 Axial distribution of acoustic pressure decay of the first diametral mode ($m = 1$) for three cavities of the same length ($L/D = 2/12$) but different depths ($h/D = 1/12, 2/12, 4/12$); x is the streamwise distance measured from the cavity center [1]

A Pitot-tube located upstream of the cavity was used to measure the flow velocity. The approach boundary layer at the cavity upstream corner was turbulent with a momentum thickness ≈ 0.8 mm and a shape factor of ≈ 1.35. Additional details of the test set-up can be found in Ref. [1].

2.2 Suppression Techniques.

Various geometries of the cavity upstream corner were investigated. These included rounding-off the corners, adding a chamfer, or saw-tooth spoilers (Fig. 3). The shapes and dimensions of these geometries are based on those of suppression devices tested previously for the case of longitudinal acoustic resonances whose wavelength is much longer than the cavity length [15–18]. In the present case, the acoustic modes are three-dimensional and the wavelength is smaller than the cavity diameter. Smith and Luloff [19] tested the effect of an upstream chamfer on the acoustic resonance of a gate valve, however, the mode shape of the acoustic mode was not defined and the effect of the chamfer was unreliable.

Two radii were used for rounding-off the corners with $r = 5.1$ and 10.2 mm ($0.2''$ and $0.4''$). The chamfers had an angle of 17 deg and two lengths of $\ell = 4.9$ and 9.8 mm ($0.19''$ and $0.38''$). The spoilers were made out of acrylic by means of a rapid prototype machine with high resolution to produce smooth surface. The high resolution of the prototype machine, the expansion ramp between the spoilers, and the short length of the spoilers (5–18 mm) minimize the effects of surface roughness if there are any. As can be seen in Fig. 4, they consisted of a chamfer $\ell = 4.9$ or 9.8 mm, and teeth to introduce three-dimensional flow disturbances at the flow separation region. The chamfer was introduced into the spoiler design to compensate the decrease in the flow area caused by the teeth, and thereby limits the increase in the pressure drop. The tested four saw-tooth spoilers differed in the number of

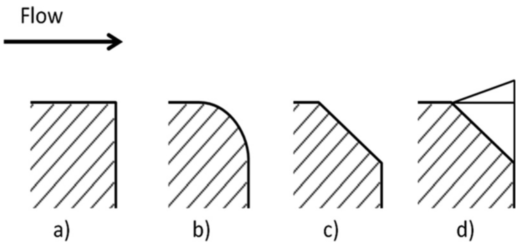

Fig. 3 Leading edge suppression techniques: (*a*) base case with no modification, (*b*) edge rounding, (*c*) chamfer, and (*d*) saw-tooth spoiler

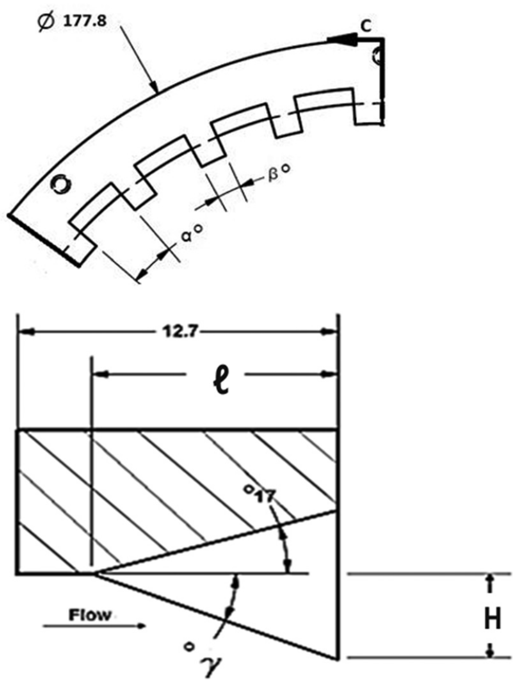

Fig. 4 Schematic of the saw-tooth spoiler (dimensions are in mm)

Table 2 Dimensions of the tested spoilers

Spoiler	α (deg)	β (deg)	T (mm)	H (mm)	γ (deg)	ℓ (mm)	Teeth
Spoiler 1	4	2	2.7	2.0	22	4.9	60
Spoiler 2	8	4	5.3	3.9	22	9.8	30
Spoiler 3	12	6	7.9	3.9	22	9.8	20
Spoiler 4	12	6	7.9	6.1	32	9.8	20

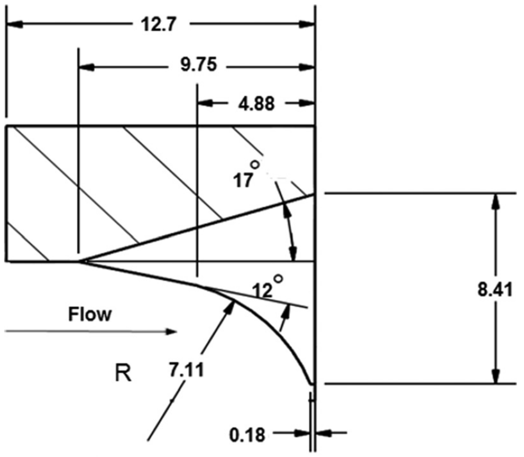

Fig. 5 Dimensions of the curved spoiler (dimensions are in mm)

teeth, and the thickness and height of the tooth. Detailed dimensions are specified in Fig. 4 and Table 2. The thickness, T, in Table 2 is measured halfway between the base and the tip of each individual spoiler.

To investigate passive suppression techniques on the more robust resonance, particularly for the deeper cavities with $h/D = 4/12$, a curved spoiler and a delta spoiler were constructed as shown in Figs. 5–7. The curved spoiler has the same parameters as spoilers 3 and 4 except that the final slope of the tooth was increased to deflect the separated flow further toward the pipe centerline.

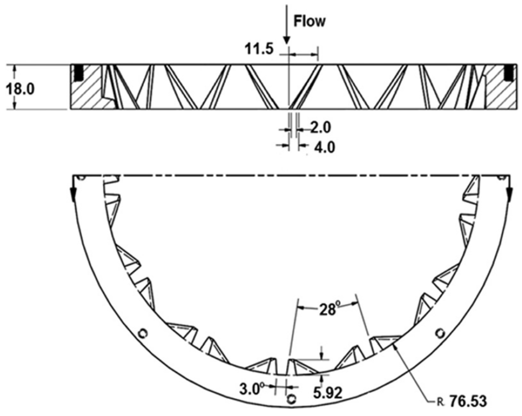

Fig. 6 Dimensions and orientation of the delta spoilers (dimensions are in mm)

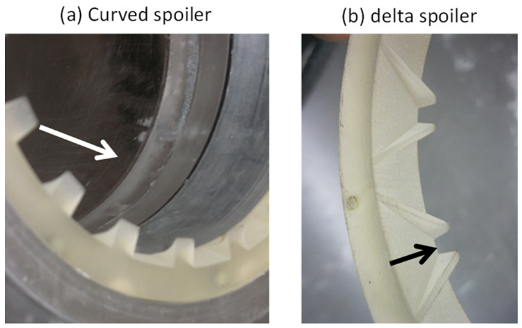
(a) Curved spoiler
(b) delta spoiler

Fig. 7 Photographs of (*a*) curved spoiler and (*b*) delta spoiler

The delta spoiler was constructed much differently from the other spoilers. This spoiler did not contain a chamfer but instead had the teeth gradually converging together as shown in Figs. 6 and 7. This allowed the introduction of a three-dimensional vorticity field at the upstream corner. Somewhat similar spoilers have previously been used to suppress longitudinal pipe resonances by flow over cavities [16].

3 Results

3.1 Effect of Chamfer and Edge Rounding-Off. For each cavity size, the base case with sharp edges was tested first and the results were used later to evaluate the performance of the suppression devices. The tests consisted of increasing the flow velocity in steps up to maximum blower capacity. The tests started with the 1 in. deep base case 3 (B3), which has $L/h = 1$ and $h/D = 2/12$.

As shown in Fig. 8, which shows the acoustic response of base case B3, several acoustic modes are excited consecutively as the flow velocity is increased. The mode order (m) indicates the number of the nodal diameters of the mode shape. The nature of these diametral modes, which are nearly trapped modes, is described in some detail in Refs. [1,2,13]. The resonances of the first three modes become particularly strong as the flow velocity exceeds 60 m/s. The excitation of the diametral modes occurs in a very organized manner and within specific ranges of Strouhal number. These aspects, together with the excitation mechanism, are described in previous papers [1–3]. It is interesting to note that as the flow velocity is increased, the acoustic resonance switches from lower to higher modes such that there is at least one mode in resonance at any flow velocity above 45 m/s and up to 140 m/s, which is the maximum capacity of the test set-up.

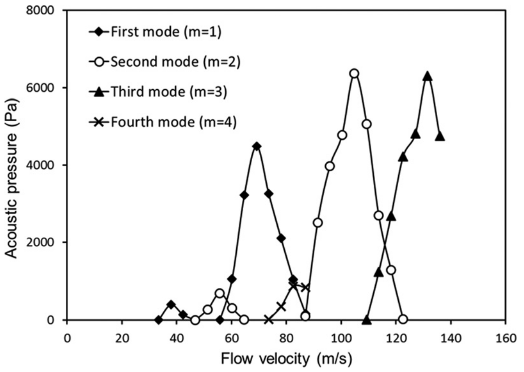

Fig. 8 Aeroacoustic response of base case B3 with sharp edges; $L/h = 1$, $h/D = 2/12$

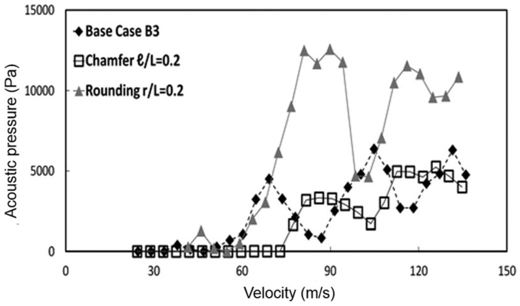

Fig. 9 Effect of the chamfer and rounding-off the edges on the acoustic resonance of base case B3; $L/h = 1$, $h/D = 2/12$

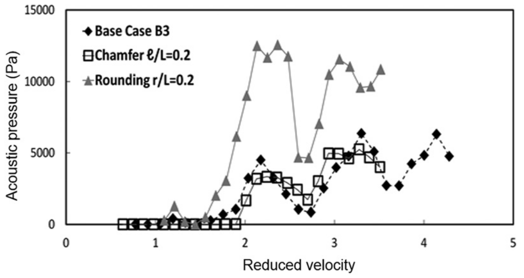

Fig. 10 Acoustic pressure verses reduced velocity showing the effect of chamfer and rounding-off the edges on the acoustic resonance of base case B3; $L/h = 1$, $h/D = 2/12$

Figure 9 is also for the base case B3 and shows the effect of rounding-off the cavity edges using a radius of $r/L = 0.2$, as well as the effect of a chamfer with $\ell/L = 0.2$ at the cavity upstream edge. For the chamfer and edge rounding, the acoustic resonance ranges, i.e., the lock-on ranges of different modes, are shifted to higher velocities. For example, while the peak of the first acoustic mode for the base case occurs around 70 m/s, the chamfer and edge rounding modifications delay it until about 85 m/s. The peak of the second mode is also delayed from ≈ 105 m/s to ≈ 115 m/s. This delay is caused by the increase in the overall (or effective) impingement length due to the additional radius of rounding-off the upstream edge and the length of the chamfer, both being 20% of the cavity length L. This apparent difference in the velocity range of resonance disappears when the reduced velocity is used to plot the data. The reduced velocity, V_r, is defined by

$$V_r = V/fL_e \tag{1}$$

where V is flow velocity, f is the dominant frequency and L_e is the equivalent cavity length $(L + r)$ or $(L + \ell)$. As can be seen in Fig. 10, the usage of the reduced velocity aligns the resonance ranges almost perfectly for first and second resonance modes in the three cases.

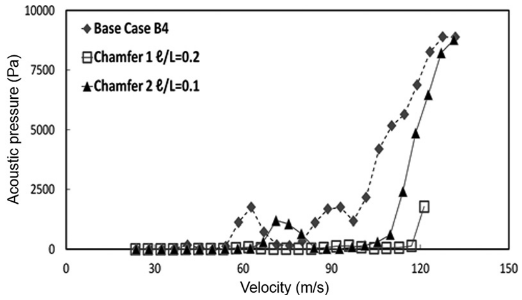

Fig. 11 Effects of chamfers on the resonance of base case B4; $L/h = 2$, $h/D = 2/12$

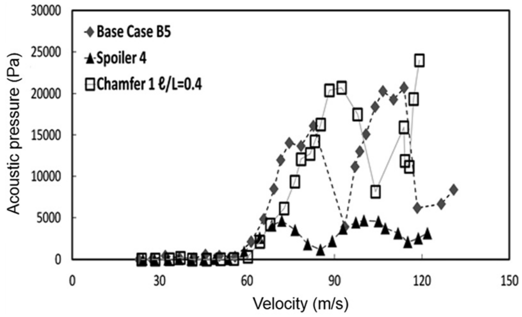

Fig. 12 Effect of chamfer ($\ell/L \approx 0.38$) and spoiler 4 on the resonance of base case B5; $L/h = 0.5$, $h/D = 4/12$

Rounding-off the edges significantly enhances the resonance in comparison with that of the chamfered and base cases. These results agree with those obtained by other researchers for the case of one-dimensional, longitudinal resonant modes with wavelength much larger than the cavity dimensions. Edge rounding is therefore not recommended as suppression technique. Although the chamfer seems to have little effect on reducing the acoustic pressure in the lock-on ranges compared with the base case, it distinctly delays the onset of resonance for the first two modes as can be seen in Fig. 9. This delay in the onset of resonance is beneficial, allowing the cavity to reach higher flow velocities without being subject to intense acoustic resonance.

Another good example is shown in Fig. 11, for the other 1 in. deep cavity (base case B4, $L/h = 2$ and $h/D = 2/12$). Here, chamfer 2 with $\ell/L \approx 0.1$ tends to suppress the acoustic resonance quite well up to 110 m/s. At this point, the acoustic resonance is initiated and the acoustic pressure reaches that of the base case. Chamfer 1, $\ell/L \approx 0.2$, does work well also; since it is longer than chamfer 2, it allows higher flow rates before reaching the onset of any significant acoustic resonance.

Additional experiments [20] showed similar results for the shallower cavities ($^1/_2$ in. deep cases B1 and B2). This is because the resonance of the shallower cavities is weaker than that of the cases B3 and B4, which have a depth of 1 in. Thus, the use of chamfers in cases B1–B4 (i.e., for cavity depth up to $h/D = 2/12$) can be beneficial if the delay in the onset of resonance allows plant operation at the maximum design flow velocity. On the other hand, when the cavity is deeper, the resonances may become stronger and the chamfer may be ineffective. An example is shown in Fig. 12 for the 2 in. deep case B5. In this case, the first mode resonance of base case B5 exceeds 1.5×10^4 Pa in comparison with 0.5×10^4 Pa for the 1 in. deep base case B3. As can be seen in Fig. 12, the chamfer neither suppresses the resonance nor delays it sufficiently to warrant it as a viable solution. In these cases which produce strong acoustic resonances, i.e., for deeper or larger cavities, a different type of suppression devices is needed. This is addressed in Sec. 3.2 which focuses on the effect of various spoilers positioned at the cavity upstream edge. However, as will be seen later, although the spoilers show better performance than the chamfer, their effectiveness deteriorates as the cavity size becomes larger.

3.2 Effect of Spoilers.

Different saw-tooth spoilers were designed and tested to investigate their effect on the acoustic resonance, particularly for the large size cavities which produce strong resonances. Unlike the effect of the chamfers, which delay the onset of resonance due to the increase in the effective cavity length, the spoilers do not affect the cavity length. Instead, they introduce a three-dimensional vorticity field at the upstream separation point of the cavity, which interferes with the self-induced disturbance generated by the acoustic particle velocity of the resonant field. If the spoiler-induced disturbances are sufficiently strong, they may disturb the organized amplification and the coherence of the shear layer oscillation and thereby alleviate the acoustic power generated by the interaction between the shear layer vorticity field and the cavity acoustic resonance. It follows that as the cavity resonance becomes stronger, its suppression would need larger spoilers to introduce larger disturbances. Additional tests were therefore performed with spoilers and cavities of different sizes to investigate these effects. The effect of saw-tooth spoilers 1 and 2 on case B3 is shown in Fig. 13. Spoiler 1, which consists of 60 small teeth of height 2 mm, managed to significantly reduce the pulsation amplitude of the first acoustic mode. However, past 90 m/s, its effectiveness deteriorated and it did little in suppressing the acoustic resonance. The larger spoiler 2, which consists of 30 teeth of height 3.9 mm, suppressed the acoustic resonance over the whole velocity range up to 130 m/s. This illustrates that the larger spoilers tend to suppress the acoustic resonance more efficiently than those of smaller dimensions. These results were further substantiated by additional tests which showed that the smallest spoiler 1 effectively suppressed the resonance of the small cavity cases B1 and B2 with $h/D = 1/12$. On the other hand, spoilers 1–3 were found to be ineffective in suppressing the resonance of the deeper cavities with $h/D = 4/12$.

Because the resonance of the deeper cavities could not be suppressed by spoilers 1–3, a larger size spoiler was designed of 20 teeth, each of which is 6.1 mm in height. The effect of this spoiler on the resonance of the deepest cavity B5 is shown in Fig. 12 in comparison with the effect of the chamfer. Spoiler 4 is much more effective than the chamfer, reducing the first mode resonance by a factor of 3 and the second mode by a factor of 4. However, since the resonance of the base cavity is very strong, reaching $\approx 2.0 \times 10^4$ Pa, the reduced amplitude when adding spoiler 4 reaches 5000 Pa, which is still substantial. Spoiler 4 was also tested with the other 2 in.-deep cavity, base case B6, and the results are given in Fig. 14. The results are similar to those of cavity B5. Spoiler 4 suppresses the weaker resonances occurring at flow velocities lower than 80 m/s. However, for the strong resonance occurring beyond this velocity, spoiler 4 reduced its amplitude from 2.5×10^4 Pa to about 8000 Pa, which may not be sufficiently small to be tolerated in industrial situations. In fact, this reduced amplitude of 8000 Pa is still higher than the maximum resonance amplitudes produced by the $^1/_2$ in. and 1 in. deep cavities (i.e., base cases B1–B4), as can be seen from Figs. 8, 11, and 13.

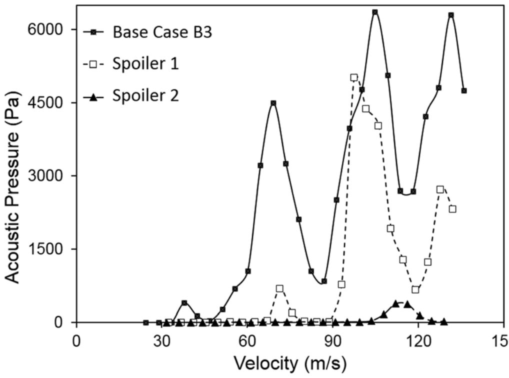

Fig. 13 Effect of spoilers 1 and 2 on the resonance of cavity case B3; $L/h = 1$, $h/D = 2/12$

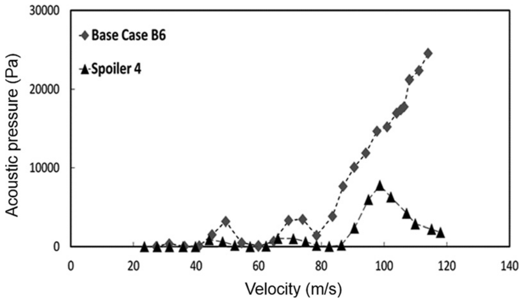

Fig. 14 Effect of spoiler 4 on the resonance of cavity B6; $L/h = 1$, $h/D = 4/12$

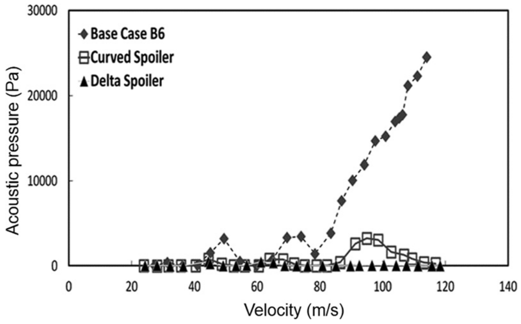

Fig. 15 Effect of the curved and delta spoilers on the resonance of cavity B6; $L/h = 1$, $h/D = 4/12$

Two additional spoiler geometries were designed to investigate whether the strongest resonance generated by the largest cavity (base case B6) can be suppressed over the whole flow range of the test set-up. The first spoiler, the curved spoiler shown in Fig. 5, is similar in size to spoiler 4, but the angle of the tooth is increased near its apex to deflect the flow at a larger angle into the center of the duct. The purpose of this design change from spoilers 3 and 4 is to increase the radial component of the flow separating from the tip of the tooth. The other spoiler is referred to as the delta spoiler and its geometry is shown in Fig. 6. The teeth of this spoiler have a height similar to that of spoiler 4, but their slanted angle relative to the axial flow direction introduces a very complex vorticity field which masks the upstream feedback generated by the resonant acoustic mode.

As can be seen in Fig. 15, the effect of the curved spoiler on the resonance of the largest cavity, case B6, is somewhat better than that of spoiler 4; it suppressed all resonances up to 85 m/s, and limited the acoustic pressure to 3000 Pa above this velocity in comparison with 8000 Pa for spoiler 4. Despite this substantial reduction in the acoustic pressure, the test results clearly illustrate the increased difficulty involved in suppressing the acoustic diametral modes as the cavity size becomes larger, which is due to the diminishing radiation losses of the resonant modes, as discussed earlier in relation to Fig. 2.

Regarding the delta spoiler, its performance proved to be superior to all other spoilers, as can be seen from Fig. 15. It suppressed all resonance modes up to 120 m/s for the two deepest cavities (B5 and B6).

As the spoilers are made larger to suppress robust resonances of large cavities, other aspects should be taken into consideration.

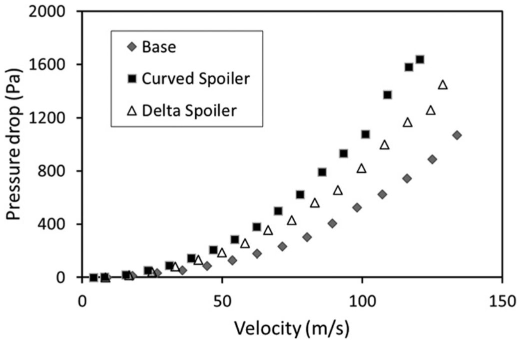

Fig. 16 Pressure drop as a function of the flow velocity measured across cavity B3 without and with curved and delta spoilers

These include the feasibility and the cost of manufacturing the spoilers, the possibility of their failure and introducing lose parts into the system, and the increase in pressure drop due to the addition of the spoilers. The latter aspect is particularly relevant for isolation gate valves because their pressure drop must be minimized when they are fully open. Figure 16 sheds some light on the increase in pressure drop caused by the curved and delta spoilers. On average, the loss coefficient ($2\Delta p/\rho V^2$) was found to be ≈ 0.081 for the base case, 0.17 for the curved spoiler and 0.13 for the delta spoiler. Thus, the curved spoiler approximately doubles the pressure drop across the cavity, in comparison with the base case, whereas the delta spoiler increases the pressure drop by only 60%. The smaller effect on the pressure drop produced by the delta spoiler, in comparison with the curved spoiler, is likely because its teeth are thinner than those forming the curved spoiler. It should be noted that the data presented in Fig. 16 were obtained from static pressure measurements at two positions located 30 cm upstream and downstream of the cavity corners.

4 Conclusions

Passive suppression techniques of the flow-excited resonance of the acoustic diametral modes of ducted cavities have been investigated experimentally. Rounding-off the cavity corners is found to slightly delay the onset of resonance because the cavity length scale (i.e., the impingement length) increases by the radius of the upstream corner. However, the ensuing resonances when the flow velocity is further increased are much stronger than those observed with sharp edged cavities. Therefore, rounding-off the corners is not recommended as a means for resonance suppression.

Similarly, adding a chamfer at the upstream corner delayed the onset of resonance in proportion to the length of the chamfer. However, the amplitude of the acoustic resonances appearing at higher velocities are comparable with those observed for sharp edged cavities. The chamfer suppression effect deteriorates as the cavity size becomes larger.

The test results indicated that as the cavity size is increased, the acoustic resonances became stronger and more difficult to suppress. For this reason, several spoilers of different sizes were designed and tested. There is always a limiting flow velocity for each spoiler size beyond which the suppression performance deteriorates. This limiting velocity is higher for larger spoilers. Of all the tested spoilers, the delta spoiler showed superior performance; suppressing all acoustic modes over the entire test range of flow velocity. However, it increases the pressure drop across the cavity by approximately 60% above that of the base case without spoilers.

References

[1] Aly, K., and Ziada, S., 2010, "Flow-Excited Resonance of Trapped Modes of Ducted Shallow Cavities," J. Fluids Struct., **26**, pp. 92–120.

[2] Aly, K., and Ziada, S., 2011, "Azimuthal Behaviour of Flow-Excited Diametral Modes of Internal Shallow Cavities," J. Sound Vib., **330**, pp. 3666–3683.

[3] Aly, K., and Ziada, S., 2012, "Effect of Mean Flow on the Trapped Modes of Internal Cavities," J. Fluids Struct., **33**, pp. 70–84.

[4] Tonon, D., Hirschberg, A., Golliard, J., and Ziada, S., 2011, "Aeroacoustics of Pipe Systems With Closed Branches," Int. J. Aeroacoustics, **10**(2), pp. 201–276.

[5] Ziada, S., and Lafon, P., 2014, "Flow-Excited Acoustic Resonance: Excitation Mechanism, Design Guidelines and Counter-Measures," ASME Appl. Mech. Rev. **66**, p. 011002.

[6] Arthurs, D., and Ziada, S., 2009, "Flow-Excited Acoustic Resonances of Coaxial Side-Branches in an Annular Duct," J. Fluids Struct., **25**, pp. 42–59.

[7] Ziada, S., and Buhlmann, E. T., 1989, "Flow Impingement as an Excitation Source in Control Valves," J. Fluids Struct., **3**, pp. 529–549.

[8] NRC, 2002, "Failure of Steam Dryer Cover Plate After a Recent Power Uprate," US Nuclear Regulatory Commission, Washington, DC, NRC Information Notice 2002-26.

[9] Howe, M. S., 1980, "The Dissipation of Sound at an Edge," J. Sound Vib., **70**, pp. 407–411.

[10] Rockwell, D., and Naudascher, E., 1978, "Review: Self- Sustaining Oscillations of Flow Past Cavities," ASME J. Fluids Eng., **100**, pp. 152–165.

[11] Evans, D. V., Levitin, M., and Vassiliev, D., 1994, "Existence Theorems for Trapped Modes," J. Fluid Mech., **261**, pp. 21–31.

[12] Kinsler, L. E., Frey, A. R., Coppens, A. B., and Sanders, J. V., 2000, *Fundamentals of Acoustics*, John Wiley & Sons, Inc., New York.

[13] Hein, S., and Koch, W., 2008, "Acoustic Resonances and Trapped Modes in Pipes and Tunnels," J. Fluid Mech., **605**, pp. 401–428.

[14] Cattafesta, L., Williams, D. R., Rowley, C. W., and Alvi, F., 2003, "Review of Active Control of Flow-Induced Cavity Resonance, AIAA Fluid Dynamics Conference, AIAA Paper No. 2003-3567.

[15] Bruggeman, J. C., Hirschberg, A., van Dongen, M. E. H., Wijnands, A. P. J., and Gorter, J., 1991, "Self-Sustained Aero-Acoustic Pulsations in Gas Transport Systems: Experimental Study of the Influence of Closed Side Branches," J. Sound Vib., **150**, pp. 371–393.

[16] Karadogan, H., and Rockwell, D., 1983, "Toward Attenuation of Self-Sustained Oscillations of a Turbulent Jet Through a Cavity," ASME J. Fluids Eng., **105**, pp. 335–340.

[17] Knotts, B. D., and Selamet, A., 2003, "Suppression of Flow-Acoustic Coupling in Side-Branch Ducts by Interface Modification," J. Sound Vib., **265**, pp. 1025–1045.

[18] Nakiboglu, G., and Hirschberg, A., 2010, "A Numerical Study of the Aeroacoustic Interaction of a Cavity With a Confined Flow: Effect of Edge Geometry in Corrugated Pipes," Proceedings of ASME 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels, FEDSM-ICNMM2010-30300.

[19] Smith, B. A., and Luloff, B. V., 2000, "The Effect of Seat Geometry on Gate Valve Noise," ASME J. Pressure Vessel Technol., **122**, pp. 401–407.

[20] Elsayed, M., 2013, "Effect of Upstream Edge Geometry on the Trapped Mode Resonance of Ducted Cavities," Master thesis, McMaster University, Hamilton, Canada.