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EFFECT OF ROUNDING-OFF THE CAVITY EDGES ON FLUID-RESONANT OSCILLATIONS OF A SHALLOW CAVITY IN A PIPE-LINE

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ABSTRACT

The effect of rounding-off the cavity edges on the fluid-resonance oscillations generated by fully developed pipe flow through an axisymmetric shallow cavity is investigated experimentally for the case of longitudinal pipe modes. Different locations of the curved edge (upstream, downstream, or both cavity corners) and different sizes of curvature are examined. The self-excited acoustic resonance is investigated by using a short piping system which is carefully designed to generate self-excited resonances. The acoustic amplitude is found to be *not significantly* affected by rounding-off the cavity edges, except for a relatively large radius. This finding is different from published results on the effects of edge curvature for other flow-sound interaction patterns. This difference in trend is due to the fact that the spatial distribution of the shear layer aeroacoustic sources in the present case is different from those observed during trapped-mode resonances in shallow cavities and in closed side-branches. In the present case, acoustic sources do exist at both the upstream and downstream corners of the cavity, whereas in the previously investigated flow geometries, an acoustic sink existed at the upstream corner and a source at the downstream corner.

Keywords: Fluid-Resonance, Cavity Flow, Cavity Edge

NOMENCLATURE

C_o	Speed of sound, (m/s)
f	Resonance frequency of the acoustic wave (Hz)
H	Cavity depth (m)
L	Cavity length in the flow direction (m)
L_{up} & L_{dn}	Upstream and downstream pipe lengths (m)
Mic1	Dynamic pressure sensor, microphone 1
Mic2	Dynamic pressure sensor, microphone 2
p	Acoustic (fluctuating) pressure (Pa)
r	Edge curvature (m)
r_{up}	Upstream edge curvature (m)
r_{dn}	Downstream edge curvature (m)
St_{L+rup}	Strouhal number, $\frac{f(L+r_{up})}{U}$
U	Mean flow velocity (m/s)
V	Cavity volume (m^3)
ρ_o	Mean fluid density (kg/m^3)
ω	Vorticity vector (s^{-1})
Γ	Vortex circulation (m^2/s)
x	Flow direction
y	cross-stream direction

INTRODUCTION

Fluid resonance oscillations in a pipe flow over a cavity depend strongly on both the shape of the acoustic mode and the cavity geometry (shallow or deep) [1–9]. Due to these variations, the effect of the curvature of cavity edges on the oscillations is different in the literature. Bruggeman et al.[10] classified the different modes of acoustic pulsations in a deep side-branch into three categories. In Case A, the acoustic pulsations are trapped between the side-branch and the upstream pipe; and in Case B, they are trapped between the side-branch and the downstream pipe (cases A and B are therefore called Trapped Modes). In Case C, the acoustic pulsations are not trapped and oscillate back and forth longitudinally between the upstream and the downstream pipe sections. According to the Bruggeman's classification, curved upstream edge in case B will have a negligible effect on the acoustic resonance, which is similar to the effect of rounding-off the downstream edge in Case A. Conversely, rounding the downstream edge in Case B or the upstream edge in Case A affects the pulsations amplitude.

Knotts and Selamet [11] examined the effect of curving both edges on the resonance response for the trapped mode in a side-branch. They found that rounding both edges caused a strong reduction in the resonance pulsation amplitude. Bolduc et al. [12] studied the effect of curving both edges on the resonance response for trapped modes of shallow cavities. Their results show amplification in the resonance amplitude with the curved edges. The above results show that the effect of rounding off the cavity edges strongly depends on both the acoustic mode pattern and the cavity type (shallow or deep). So the objective of this work is to investigate the effect of rounding-off the cavity edges on the resonance response of the longitudinal acoustic mode excited by flow over a shallow cavity.

TEST SETUP

A short piping system was carefully designed in order to generate self-excited resonances within a suitable velocity range and to reduce the viscous losses in order to easily sustain acoustic resonances as shown in Fig. 1. The cavity in this design was centered between two pipe sections of 0.65m long each. The acoustic (fluctuating) pressure inside the pipeline was measured by means of two 1/4" GRAS 40BP condenser microphones with a sensitivity of 1.6 mV/Pa and an uncertainty of 0.25 Pascal in the measurement frequency range. The maximum measured dynamic (rms) pressure is about 600 Pascal. Hence, the relative uncertainty of the acoustic pressure dp/p is about ± 0.042%. For the longitudinal (plane) standing sound wave inside the pipe, the acoustic pressure is uniform over any cross-sectional plane of the pipe but only changes along the pipe axis. Therefore, the microphones were flush mounted at specified locations along the pipe top wall. The first microphone was located at the peak location of the sound pressure standing wave of the first harmonic mode (middle of the downstream pipe section) and the second microphone was located at the peak of the second harmonic mode (a quarter of the downstream pipe length from the outlet section). The flow velocity at the centerline of the pipe was measured by means of a pitot tube which was connected to a Validyne differential pressure transducer of model number DP15-42 which has an accuracy of ± 0.25% of the full scale. Therefore, the relative uncertainty of the mean flow velocity dU/U is ± 0.125% and the relative uncertainty of the speed of sound dC/Co is about ± 0.025%. From the measured quantities, the normalized self-excited resonance amplitude, $p/\rho_o C_o U$. was calculated where p is the dynamic (rms) acoustic pressure, ρ_o and Co are the density and speed of sound in air, and U is the mean flow velocity in the pipe measured by the pitot tube and adjusted to the value at the leading edge of the cavity [13,14]. The relative uncertainty of the normalized self-excited resonance amplitudes is ± 0.134%.

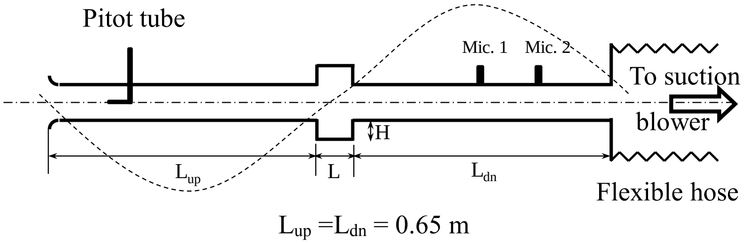

FIGURE 1: TEST SETUP FOR THE SELF-EXCITED FLUID-RESONANCE OSCILLATIONS

The blower speed controller was used to operate the system at different values of the flow velocity U while the two microphone signals were recorded for 60 seconds and then averaged to get the frequency spectrum at each flow velocity. From the spectrum, the resonance lock-in velocity ranges, and the peak amplitude of different harmonic modes were investigated. One shallow cavity size was selected (78 mm long, L, by 26 mm deep, H) to be tested with different combinations and sizes of edge curvatures r_{up} and r_{dn}. Table 1 and Fig. 2 show the combinations and sizes of edge curvatures that are studied.

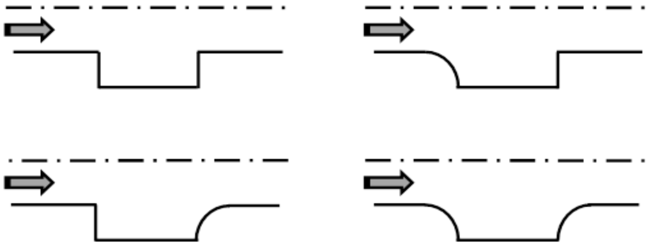

FIGURE 2: STUDIED CASES OF ROUNDED EDGES

TABLE 1: TESTED CAVITIES WITH ROUNDED-OFF EDGES

Description	Upstream edge curvature r_{up}/H	downstream edge curvature r_{dn}/H
Sharp-Sharp	0	0
Curved-Sharp	20%, 40%, 100%	0
Sharp-Curved	0	20%, 40%, 100%
Curved-Curved	20%, 40%, 100%	20%, 40%, 100%

RESULTS

Figs. 3 and 4 present the effect of the edge curvature on the normalized self-excited resonance amplitude against the normalized velocity or Strouhal number, St_{L+rup}:

$$St_{L+rup} = f\,(L+r_{up})\,/\,U. \qquad (1)$$

According to the fluid-resonant oscillations, the timing of the interaction between the acoustic field and the free shear layer at the leading edge is the key characteristic that can lead to magnify or dampen the oscillation. So, the characteristic length was selected as the cavity length plus the radius of the upstream corner[15,8]. In Fig. 3, the effects of the location and curvature size of the curved edge(s) on the normalized self-excited resonance amplitude are illustrated for the four possible cases; sharp-sharp, curved-sharp, sharp-curved, and curved-curved, as well as for three curvature sizes (r/H = 20%, 40%, and 100%) for the cavity size of 78 mm long and 26 mm deep.

From Fig. 3, one can observe that whatever the size of the curvature, the cavity with a curved upstream edge and sharp downstream edge has the highest normalized resonance amplitude ratio followed by the sharp-sharp then the sharp-curved cases while the lowest resonance amplitude ratio is for the curved-curved case. This reduction in the normalized resonance amplitude from the strongest to the weakest resonance cases is around 15-20% for r/H values of 20 and 40% (top and middle insets of Fig. 3), but for the case of r/H = 100%, the maximum reduction is about 40% (bottom inset of Fig. 3).

From the top inset of Fig. 4 for different curvature sizes of the sharp-curved case, as the downstream edge curvature size increases, the resonance amplitude slightly decreases, and the maximum reduction is about 20% at the fully curved case, r_{dn}/H equals 100%. The middle inset of Fig. 4 (all sizes of the curved-sharp case), as the upstream edge curvature size increases, the resonance amplitude slightly increases and then saturates. The maximum increase is about 16%. According to the bottom inset of Fig. 4 for different curvature sizes of the curved-curved case, as the edges curvature size increases, the resonance amplitude slightly decrease till r/H = 40% and then a maximum reduction of about 30% occurs for the case of r/H = 100%.

In general, based on these results, there are no significant effects of the upstream or downstream edge curvature on the normalized acoustic resonance amplitude for the case of shallow cavity coupled with longitudinal acoustic mode except for relatively large radius. This finding is totally different from published results on the effects of edge curvature for the cases of side-branches and shallow cavities coupled with trapped acoustic modes which were investigated in previous works [10–12].

DISCUSSION

The observed different effect of rounding-off the cavity edges is expected as the spatial distribution of the aeroacoustic sources in the present case is found to be different from those observed in previous studies. Mohamed and Ziada [2,16,7] experimentally investigated the spatial distribution of the acoustic power at peak of resonance condition using PIV flow measurements and finite element simulations of the acoustic mode combined into Howe's aeroacoustic integrand. The spatial distribution of the acoustic power resulting from the cavity shear layer interaction with the longitudinal sound wave in a pipeline at peak of resonance condition showed an acoustic power generation source (+) at the first and the last thirds of the cavity length and an acoustic power absorption sink (-) in the middle third as shown in Fig. 5. This distribution is different than the spatial distribution of the acoustic power in side branches with trapped acoustic mode which has acoustic power absorption sink (-) at the first half of the cavity length and an acoustic power generation source (+) in the second half. These different acoustic power spatial distributions for different flow-sound-structure interaction cause the difference in the effect of rounding off the cavity edges from case to another

In order to identify the controlling variable of the aeroacoustic power in this type of flow and geometry, Howe [17] showed that the instantaneous acoustic power P in a non-vanishing vorticity field within a volume V is proportional to the triple product of the vorticity ω, flow velocity U, and acoustic particle velocity υ as presented in Eqn. 2.

$$P = -\rho_o \int \omega \cdot (U \times \upsilon)\, dV \qquad (2)$$

The discrete vortex model proposed by Nelson et al. [18] considers the vorticity in the free shear layer to be concentrated into point vortices traveling with an approximately constant phase speed along the cavity mouth ($U_c/U = 1/2$). Thus, the vorticity vector ω in Howe's integrand may be replaced by the circulation of the vortex Γ which can be approximately estimated from the flow velocity and the acoustic wave frequency as follow [19]:

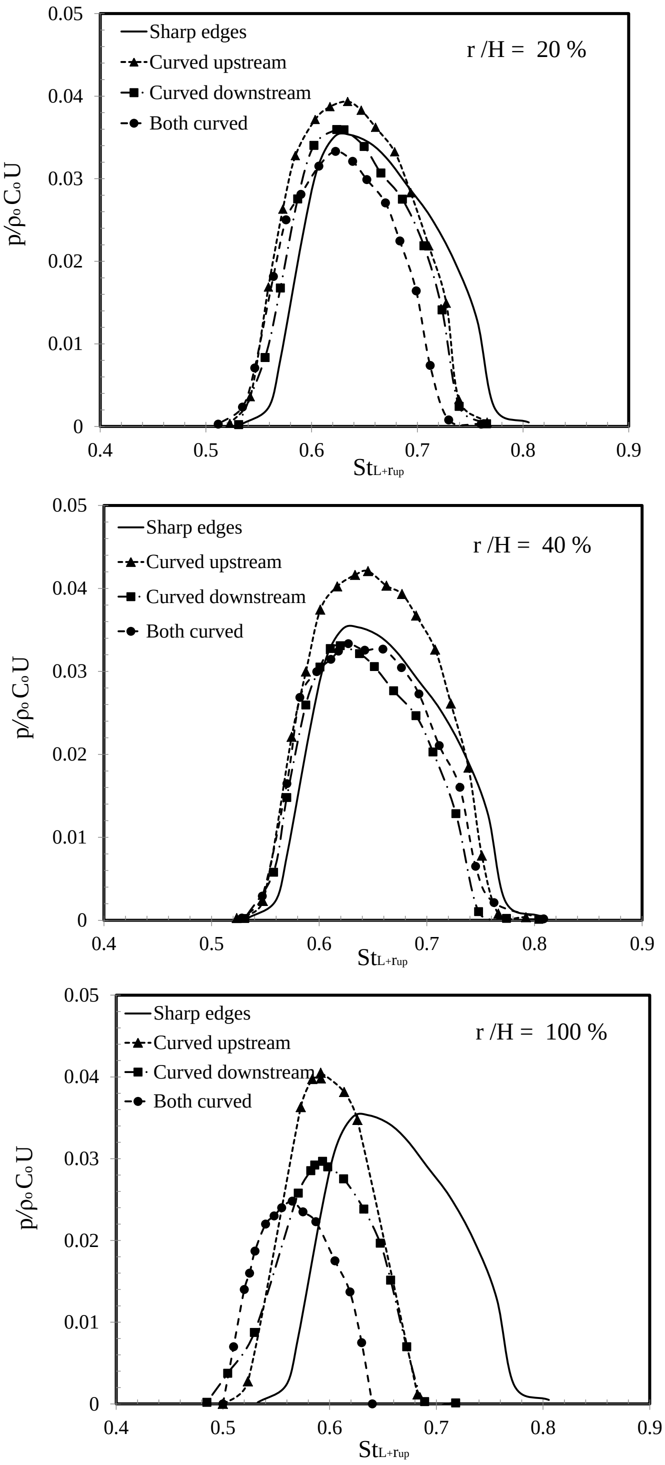

FIGURE 3: EFFECT OF THE LOCATION OF THE CURVED EDGE(S) ON THE NORMALIZED SELF-EXCITED RESONANCE AMPLITUDE. THREE CURVATURE SIZES WERE TESTED (r/H = 20%, 40%, AND 100%)

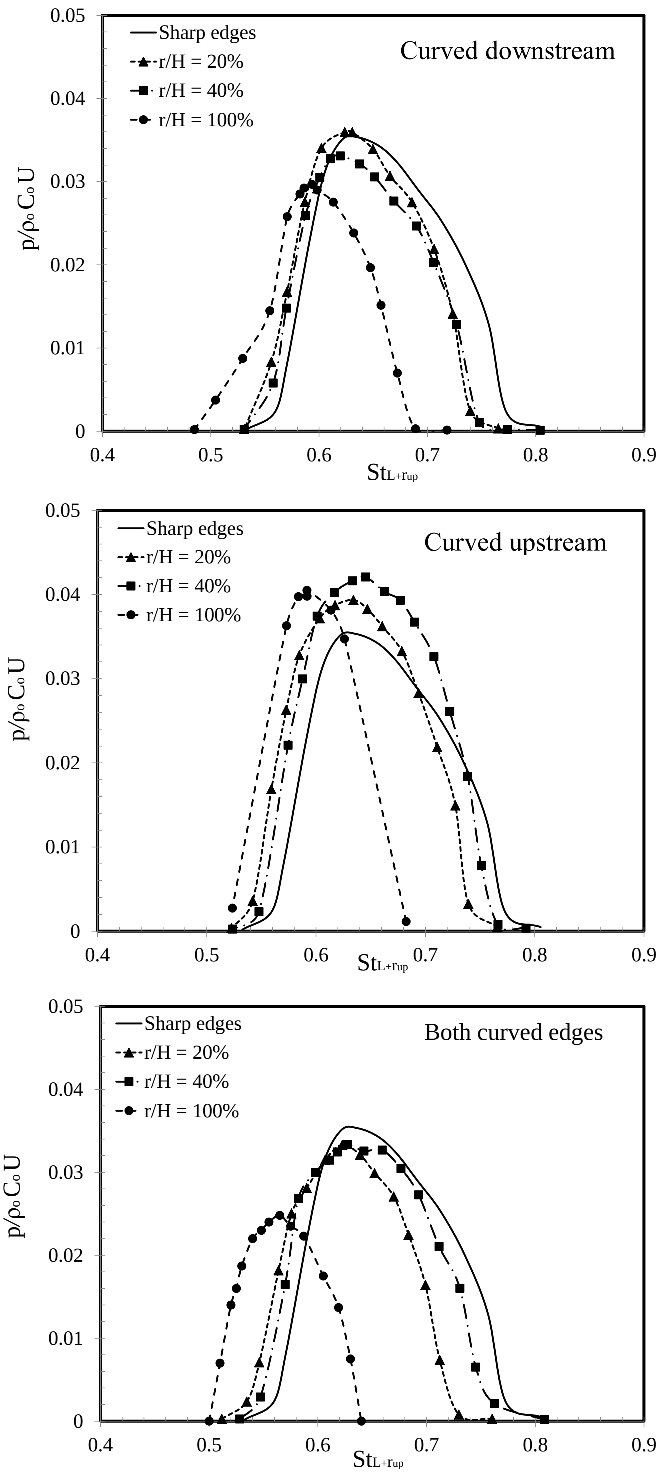

FIGURE 4: EFFECT OF THE EDGE CURVATURE SIZE ON THE NORMALIZED SELF-EXCITED RESONANCE AMPLITUDE. THREE CURVATURE SIZES WERE TESTED (r/H = 20%, 40%, AND 100%)

$$\Gamma = U \times \frac{U}{2} \times \frac{1}{f} \qquad (3)$$

The cross product $(U \times \upsilon)$ in Eqn. 2 can be rearranged for 2-D flow as follows:

$$(U \times \upsilon) = U_x \upsilon_y - U_y \upsilon_x \qquad (4)$$

where $U = U_x\, i + U_y\, j$ and $\upsilon = \upsilon_x\, i + \upsilon_y\, j$; x is the flow direction and y is the cross-stream direction. By considering the main flow to be in the x-direction or $U_x >> U_y$, the acoustic power is expected to be strongly affected by the term $(U_x\, \upsilon_y)$. As the relative change in U_x, which is $\Delta Ux/Ux$, is very small compared to the relative change in υ_y at the cavity mouth, the parameter with the strongest influence on aeroacoustic power generation appears to be the cross-stream component of the acoustic particle velocity field, υ_y.

In order to scrutinize the cross-stream component of the acoustic particle velocity in the cavity region and how it is affected by rounding-off the cavity edges, the finite element technique using ABAQUS was employed to obtain the acoustic pressure distribution of the resonant acoustic mode and a MATLAB code solving Euler's equation was used to compute the acoustic particle velocity field and the streamlines for different locations of curved edges. More details on the finite element simulation as well as the mesh size, type, and boundary conditions are available in Mohamed [2].

Fig. 6 shows the acoustic particle velocity streamlines for different locations of the curved edge. The curved edge seems to reduce the vertical component of the acoustic velocity as the streamlines have more space for gradual change than in the case of the sharp-edged cavity. On the other hand, the curved edge increases the length over which the source power is integrated. These two opposite effects make the overall influence of the curved edges on the normalized self-excited resonance amplitude insignificant except for the fully curved edges.

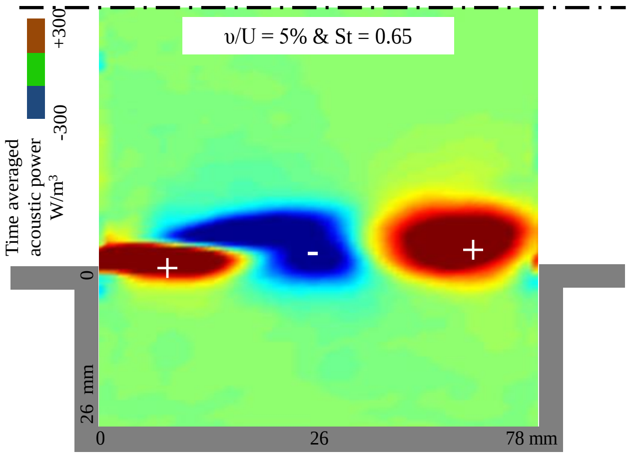

FIGURE 5: THE SPATIAL DISTRIBUTION OF THE ACOUSTIC POWER RESULTING FROM THE CAVITY SHEAR LAYER INTERACTION WITH THE LONGITUDINAL SOUND WAVE IN A PIPELINE [2].

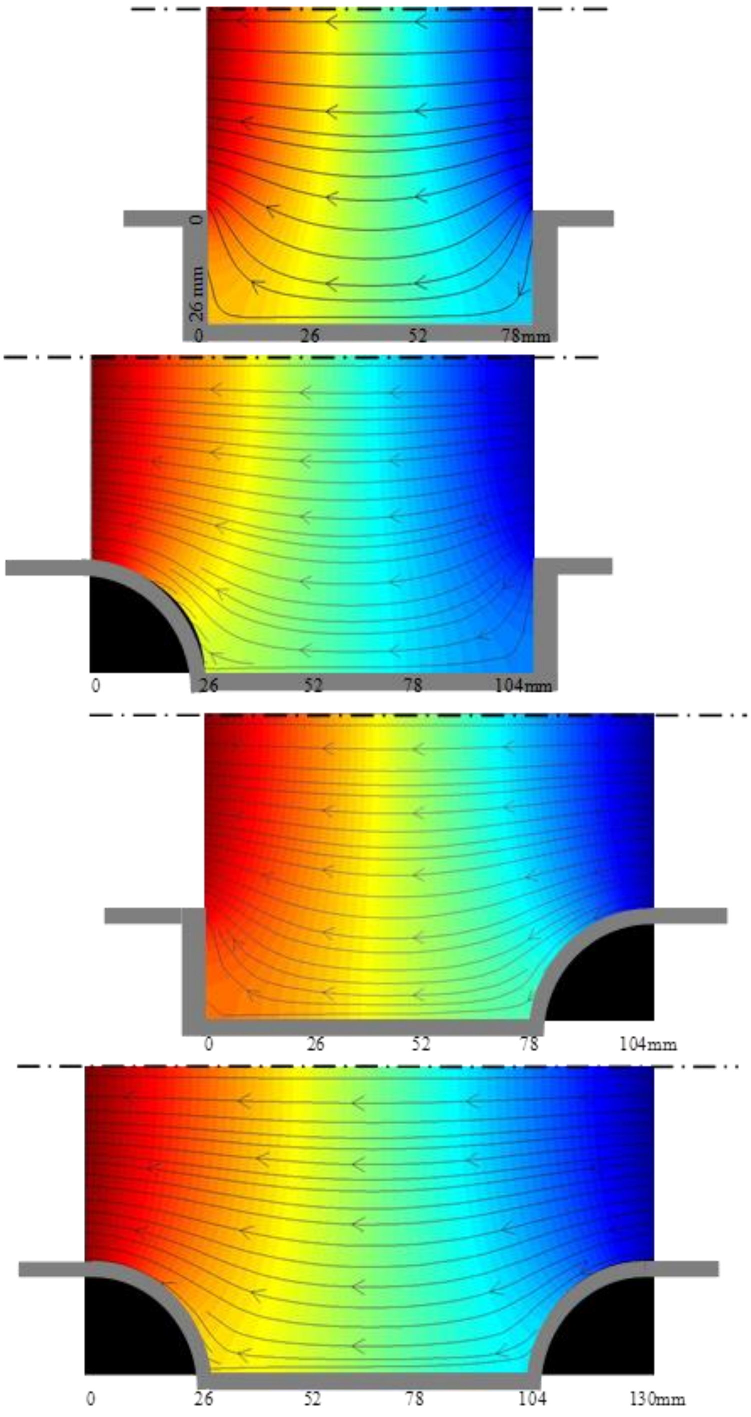

FIGURE 6: EFFECT OF LOCATION OF THE CURVED EDGE ON THE ACOUSTIC PARTICLE VELOCITY STREAMLINES FOR CAVITY OF 78 MM X 26 MM.

CONCLUSION

A comprehensive study of the effects of rounding-off the cavity edges is presented. From this study, rounding-off the cavity edges causes a reduction in the vertical component of the acoustic particle velocity that leads to a reduction in the acoustic power. However, increasing the cavity length provides a larger volume over which the acoustic power is integrated which increases the acoustic power. These opposite effects cancel out and therefore the acoustic amplitude is not significantly affected by rounding-off the cavity edges, except for relatively large radius. This finding is different from published results on the effects of edge curvature for other flow-sound interaction patterns. This difference is attributed to variations between the spatial distribution of the aeroacoustic sources in the present case and the distributions observed for other flow geometries.

REFERENCES

[1] Mohamed, S., Graf, H., and Ziada, S., 2018, "Measurement of the Excitation Source of an Axisymmetric Shallow Cavity Shear Layer," *Journal of Pressure Vessel Technology*, **140**(June), pp. 1–12.

[2] Mohamed, S., 2015, "Sound Waves Excitation by Flow in a Pipe Housing a Shallow Cavity," McMaster University, Ph.D. Thesis.

[3] Graf, H. R., and Ziada, S., 2010, "Excitation Source of a Side-Branch Shear Layer," *Journal of Sound and Vibration*, **329**(14), pp. 2825–2842.

[4] Salt, E., Mohamed, S., Arthurs, D., and Ziada, S., 2014, "Aeroacoustic Sources Generated by Flow-Sound Interaction in a T-Junction," *Journal of Fluids and Structures*, **51**, pp. 116–131.

[5] Ziada, S., 1994, "A Flow Visualization Study of Flow-Acoustic Coupling at the Mouth of a Resonant Side-Branch," *Journal of Fluids and Structures*, **8**(4), pp. 391–416.

[6] Mohamed, S., and Ziada, S., 2018, "PIV Measurements of Aeroacoustic Sources of a Shallow Cavity in a Pipeline," *Journal of Pressure Vessel Technology*, p. doi:10.1115/1.4039920.

[7] Mohamed, S., and Ziada, S., 2015, "Effect of Cavity Volume on the Flow-Excited Acoustic Resonance of a Shallow Cavity in a Pipe-Line," *ASME Pressure Vessels and Piping Conference, Fluid-Structure Interaction*, **4**.

[8] Nakiboğlu, G., Manders, H. B. M., and Hirschberg, a., 2012, "Aeroacoustic Power Generated by a Compact Axisymmetric Cavity: Prediction of Self-Sustained Oscillation and Influence of the Depth," *Journal of Fluid Mechanics*, **703**, pp. 163–191.

[9] Nakiboğlu, 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," *FEDSM2010*, **3**, pp. 767–773.

[10] 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," *Journal of Sound and Vibration*, **150**(3), pp. 371–393.

[11] Knotts, B. D., and Selamet, a., 2003, "Suppression of Flow-Acoustic Coupling in Sidebranch Ducts by Interface Modification," *Journal of Sound and Vibration*, **265**(5), pp. 1025–1045.

[12] Bolduc, M., Ziada, S., and Lafon, P., 2016, "On The Modal Behaviour of Trapped Acoustic Modes in a Square Ducted Cavity," *22nd AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics.

[13] Doherty, J., Monty, J., and Chong, M., 2007, "The Development of Turbulent Pipe Flow," *Australasian Fluid Mechanics Conference*, pp. 266–270.

[14] White, F. M., and Corfield, I., 2006, *Viscous Fluid Flow*, McGraw-Hill Higher Education Boston.

[15] Bruggeman, J., 1987, "Flow Induced Pulsations in Pipe Systems," *Ph.D. Thesis Technische Hogeschool, Eindhoven (Netherlands).*

[16] Mohamed, S., and Ziada, S., 2014, "PIV Measurements of Aeroacoustic Sources of a Shallow Cavity in a Pipeline," *ASME Pressure Vessels and Piping Conference, Fluid-Structure Interaction*, **4**.

[17] Howe, M. S., 1975, "Contributions to the Theory of Aerodynamic Sound, with Application to Excess Jet Noise and the Theory of the Flute," *Journal of Fluid Mechanics*, **71**(4), p. 625.

[18] Nelson, P. A., Halliwell, N. A., and Doak, P. E., 1983, "Fluid Dynamics of a Flow Excited Resonance, Part II: Flow Acoustic Interaction," *Journal of Sound and Vibration*, **91**, pp. 375–402.

[19] Howe, M. S., 1998, *Acoustics of Fluid-Structure Interactions*, Cambridge University Press, Cambridge.