EFFECT OF CAVITY DEPTH ON DIAMETRAL MODES EXCITATION

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ABSTRACT

The effect of cavity depth on the aerodynamic excitation of the diametral acoustic modes of an axisymmetric shallow cavity in a duct is investigated experimentally. Numerical simulations of the mode shapes are also performed to investigate the effect of the cavity depth on the mode shapes. Three cavity depths and six different cavity lengths for each cavity depth are investigated. The aeroacoustic response of the cavity-pipe system is studied up to a Mach number of 0.4. The diametral acoustic modes are strongly excited for all the tested cases. The amplitude of excitation increases with the cavity depth as a result of the increase in the radial component of acoustic particle velocity. The susceptibility of different acoustic modes to aerodynamic excitation and the dependence of mode selectivity at resonance on the cavity depth is also discussed.

1. INTRODUCTION

Flow over cavities is well known to be a potential source of acoustic resonance excitation in numerous engineering applications. Flow-excited acoustic resonances can cause hazardous noise level, significant alteration of the operating conditions and, in some cases, can result in catastrophic failure due to acoustic fatigue of the cavity structure.

Flow over cavities has been extensively investigated to understand the physics and determine the parameters controlling the phenomenon. It is generally accepted that the mechanism controlling cavity oscillation consists of two main components: the inherent instability of the cavity shear layer and an upstream feedback phenomenon. In this study, the feedback effect is provided by the acoustic resonance of a shallow cavity in a duct. The shear layer instability causes small vorticity perturbations at the cavity leading edge to grow rapidly as they travel downstream. As these amplified vorticity perturbations reach the cavity downstream corner, a small portion of the flow perturbation energy is transferred into acoustic energy to sustain the acoustic resonance, which, in turn, generates a strong vorticity fluctuation at the upstream separation region of the shear layer. This mutual interaction, which constitutes the fluid-resonant feedback phenomenon, induces a relatively high level of initial perturbations in the free-shear layer (Rockwell & Naudascher, 1978).

The aforementioned description of the feedback mechanism underlines the importance of the acoustic resonance in the process. The investigation presented in this paper focuses on the excitation of the trapped acoustic modes, also called the cross-modes, of a cavity-duct system. Only few studies investigated the excitation of duct trapped modes by flow over shallow cavities. The presence of a cavity onto the duct wall lowers the frequencies of the cross-modes below the cutoff frequencies of the main duct. According to Kinsler et al. (2000) , these modes consist of transverse standing waves, which do not propagate down the duct, and their amplitude decays exponentially with the distance along the duct. Therefore, these modes are “locked” to the cavity and experience relatively low acoustic radiation into the duct.

Ziada et al. (2003) have studied the excitation of these modes by flow over a two-dimensional shallow cavity mounted onto a rectangular duct. It was clear from the reported results that the transverse modes are excited by the cavity shear layer. Keller & Escudier (1983) have performed a limited number of tests on an axisymmetric cavity using a blow-down wind tunnel. They reported resonance of a diametral acoustic mode at a very high transonic flow speed. No details had been given about the flow conditions over which the diametral mode was excited.

The objective of the present work is to investigate the effect of cavity depth on flow excitation of the diametral modes of an axisymmetric pipe-cavity system. Different cavity depths and lengths are tested up to a Mach number of 0.4. Numerical simulations are also performed to determine the effect of the cavity depth on the acoustic mode shapes. The simulation results are then used to explain some of the experimental observations, such as the dependence of excitation level and mode selectivity at resonance on the cavity depth.

2. EXPERIMENTAL SETUP

2.1 Test facility

The tests are conducted using an open loop wind tunnel. The tunnel is equipped with a centrifugal blower powered by 50 hp motor. The flow rate through the wind tunnel is changed by varying the blower speed using a variable driving speed control unit. This setup is capable of producing a flow velocity in the test section of around 150 m/s at the blower maximum rotational speed. The test section is connected to the suction side of the blower by means of a conical diffuser to reduce flow losses and facilitate tests at high flow velocities. A parabolic axisymmetric contraction was attached to the test-section inlet to produce uniform velocity profile.

Figure 1 shows a schematic of the test section geometry. The test section consists of two 150 mm in diameter clear acrylic pipes. Each pipe is 450 mm long, with 6.25 mm wall. The connection between the two pipes has a larger diameter to form an axisymmetric internal cavity. Acrylic flanges of various dimensions are use in different combinations to form the desired cavity size and ensure that the pressure sensors are located at the centre of the cavity. As shown in Table 1, three cavity depths are investigated (d = 12.5, 25 and 50 mm), and for each depth, several length to depth ratio (L/d) are tested. O-rings are used to seal all the interfaces between the flanges. This prevents air leakage from or to the test section and thereby precludes acoustic losses that would result from air leakage.

Table 1: Dimensions of tested cavities.

D (mm)	Ratio d/D	Tested ratios of L/d
12.5	1/12	2, 4, 6, 8, 10, 12
25	2/12	1, 2, 3, 4, 5, 6
50	4/12	0.5, 1, 1.5, 2, 2.5, 3

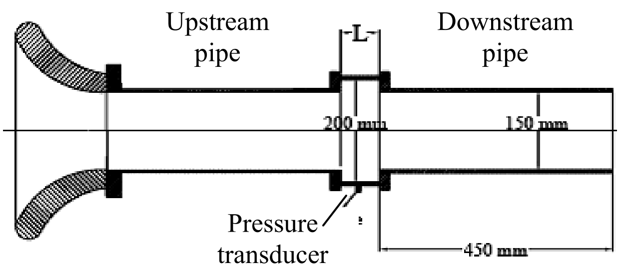

Figure 1: Schematic drawing of the test section.

2.2 Instrumentation

The test program included measurements of the mean flow velocity and the acoustic pressure. The data acquisition system that was used to acquire the data consisted of a 16-bit, 4-channel, National Instrument card model PCI-4452, and was equipped with anti-aliasing filter. Labview program was used for data acquisition and analysis.

The mean flow velocity was measured using a static pitot tube that was located directly downstream the bell mouth contraction. Measurements at this location provided the average mean flow velocity before the developing of the boundary layer. A differential pressure transducer was used to determine the dynamic head.

Multiple pressure transducers were used to obtain the instantaneous acoustic pressure simultaneously at different physical angles around the circumference of the cavity floor. The pressure transducers were flush mounted to the inside surface of the cavity floor. The pressure transducers were equipped with acceleration-compensating sensor to eliminate the effect of vibration on the pressure signal. Spectra of the pressure transducers were averaged over 40 data samples, each of which is one second long. The time signals were sampled at a frequency of 32 kHz, yielding a frequency resolution of one Hertz.

3. DIAMETRAL ACOUSTIC MODES

A set of numerical simulations was conducted to provide insight into the characteristic of the diametral acoustic modes of the pipe-cavity system. Finite element commercial package "ABAQUS" was used to conduct the simulations. The boundary conditions at the pipe ends were set to zero acoustic pressure to simulate open ends. Figure 2 shows the mode shape of the first diametral acoustic mode for a cavity with d/D=2/12 and L/d = 1 attached to 450 mm long pipes at both ends. The diametral modes are shown in the form of normalized acoustic pressure contours. The bright and dark contours have opposite signs to indicate that they are out of phase. It is clear from Fig. 2 that the diametral modes are locked to the cavity and the acoustic pressure decays exponentially in the axial direction. For all the diametral modes, the maximum acoustic pressure occurs at the cavity floor and midway along its length. The pressure transducers were therefore installed at these locations. Also, the acoustic pressure varies in the form of a sine wave distribution along the cavity circumference and the number of the complete sine wave cycles formed by the acoustic pressure over the circumference is equal to the mode number.

An important feature of the acoustic mode shape is the distribution of the acoustic particle velocity. Figure 3 shows the vector plot of the acoustic

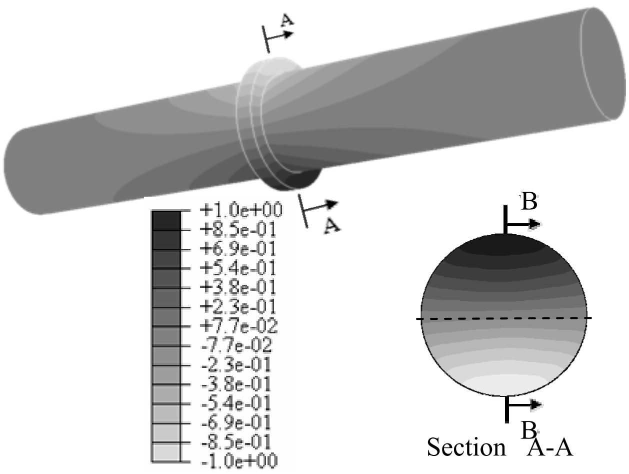

Figure 2: *The mode shape of the first diametral acoustic resonance in terms of pressure contours (d/D=2/12, L/d=1)*

particle velocity over the cross section B-B shown in fig. 2. From the vector plot, it can be seen that the maximum particle velocity is at the centerline of the pipe and it decreases in the direction towards the pipe wall. In this paper, attention is focused on the amplitude of the acoustic particle velocity along the mouth of the cavity where the shear layer is formed. This is because the vorticity-based contribution to acoustic power generation is linearly proportional to the acoustic particle velocity (Howe, 1975); and the acoustic power is produced within the region encompassing the cavity free shear layer.

Figure 4 shows the radial component of the acoustic particle velocity amplitude over the cavity mouth for L/d=1, 3 and 6. These particle velocity amplitudes correspond to a maximum acoustic pressure of one Pascal at the centre of the cavity floor. The average amplitudes of the radial acoustic particle velocity along the cavity mouth are 1.09, 1.06 and 1.00 mm/s for L/d=1, 3 and 6, respectively. This indicates that the length of the cavity has no major effect on the amplitude of the

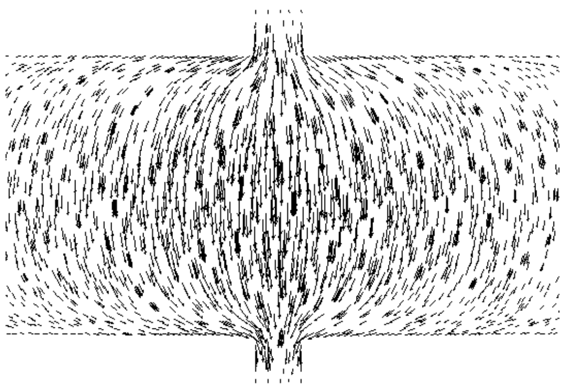

Figure 3: *Vector plot of the acoustic particle velocity amplitude of the first diametral mode (d/D=2/12, L/d=1)*

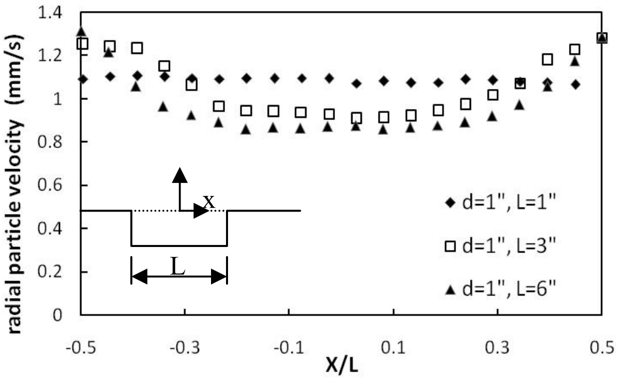

Figure 4: *Radial component of the acoustic particle velocity along the cavity mouth*

acoustic particle velocity. In the rest of the paper, the average amplitude of the radial acoustic particle velocity is used without presenting the complete distribution over the cavity mouth.

4. GENERAL SYSTEM RESPONSE

Before presenting the effect of changing the cavity dimensions on the system response, a typical system response is briefly presented. Figure 5 shows the dominant acoustic modes as a function of the flow velocity for a cavity with L/d=1 and d/D=1/6. The data show upward and downward frequency jumps, from one acoustic mode to another, as the velocity is increased. This behaviour exemplifies the general trend of cavity-excited resonance as reported by, for example, Schachenmann & Rockwell (1980). In general, the first and second free shear layer modes (n=1,2) excite the first four diametral modes (r=1-4), alternatively. However, the third free shear layer mode (n=3) excites the third diametral mode strongly over a very narrow velocity range around 40m/s. These results suggest that the higher order acoustic modes are suppressed if another lower

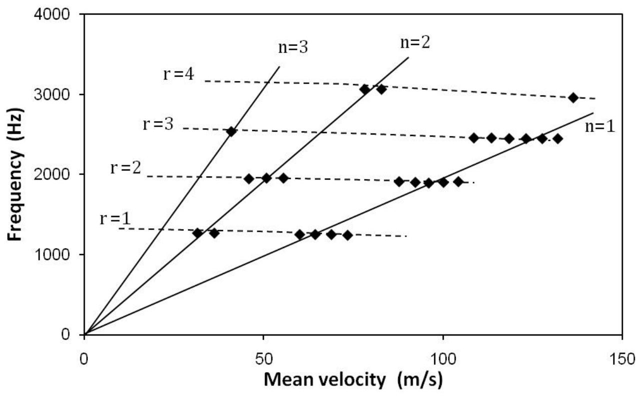

Figure 5: *Frequency of the dominant diametral acoustic modes at different velocities. (r is the acoustic mode number and n is the free shear layer mode number)*

order mode is excited by a lower order cavity shear layer mode. For example, between 60-70m/s, the third diametral acoustic mode is not excited because the first acoustic mode (r=1) is excited strongly by the first shear layer mode (n=1).

Figure 6 shows the dimensionless acoustic pressure amplitude of the dominant diametral acoustic modes against the Strouhal number. The RMS amplitude of acoustic pressure is normalized by the dynamic head of the mean flow ($1/2\rho U^2$). The Strouhal number, $f_r L/U$, is based on the cavity length, L, the resonance mode frequency, f_r, and the mean flow velocity, U. Figure 6 shows that the Strouhal number at which a particular shear layer mode excites various acoustic modes (r=1 to 4) is almost constant. The first and second cavity free shear layer modes (n = 1,2) have Strouhal numbers near 0.5 and 1, respectively. Note that the Strouhal number for any mode is taken as the Strouhal number at the maximum dimensionless pressure amplitude for this mode. For the purpose of comparison in the upcoming section, the maximum dimensionless pressure produced by a certain shear layer mode is used as an indication of the strength of the excitation level.

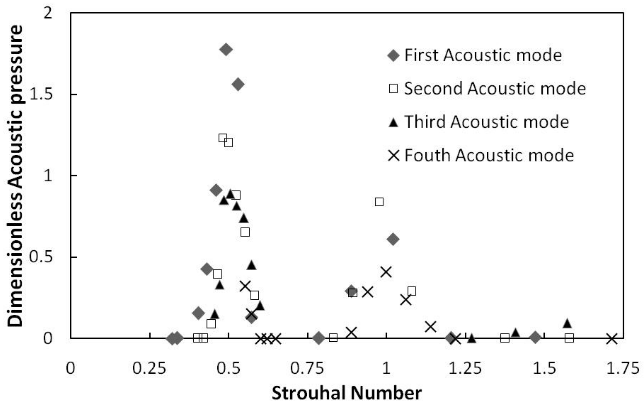

Figure 6 : *Dimensionless pressure as a function of the Strouhal number (L/d=1, d/D=2/12)*

5. EFFECT OF CAVITY DEPTH ON SYSTEM BEHAVIOUR

Changes in the cavity depth (d) affect, to varying degrees, the main features of the system response; including the cavity free shear layer Strouhal number, the level of acoustic excitation and the susceptibility of various acoustic modes to excitation. The effect on the Strouhal number depends on the cavity length to depth ratio, rather than on the depth alone. This effect is not discussed here because it has been investigated in detail by other researchers as summarized by Rockwell & Naudascher (1978). The objective of the present work is to shed more light onto the effect of cavity depth on the excitation level and the mechanism of mode selectivity of acoustic resonance. First, the results showing the effect of the cavity depth on the excitation level are discussed. Thereafter, a numerical simulation study is performed to investigate the effect of the cavity depth on the acoustic mode shapes and the associated distributions of the acoustic particle velocity. These particle velocity distributions are then used to explain the susceptibility of different diametral modes to flow excitation and also to clarify the phenomenon of mode selectivity as observed during the present experiments.

5.1 Effect of cavity depth on excitation level

The excitation level, and consequently the amplitude of the acoustic pressure, is found to be strongly dependent on the cavity depth, or in other words, it depends on the cavity depth to the pipe diameter ratio (d/D). Figure 7 shows the maximum dimensionless acoustic pressure of the lowest diametral mode (r = 1) when excited by the first shear layer mode (fig. 7a) and by the second shear layer mode (fig. 7b). The results are given for the three tested cavity depths (d/D), and the cavity length is taken as a parameter. It is evident that the ratio d/D has substantial effect on the excitation

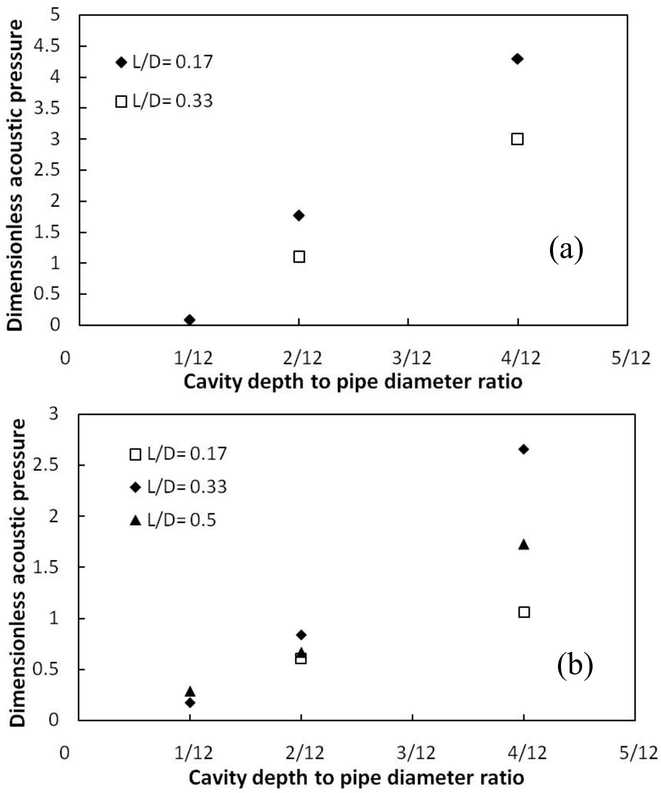

Figure 7: *Maximum dimensionless acoustic pressure for different cavity depths to pipe diameter ratio a) excitation by cavity first free shear layer mode, b) excitation by cavity second free shear layer mode*

level of the diametral acoustic modes. The maximum dimensionless acoustic pressure achieved for (d/D)=4/12 is an order of magnitude higher than that observed for (d/D)=1/12. The trend shown in fig. 7 indicates that a further decrease in the cavity depth may suppress the diametral mode resonance altogether. Based on the available results, this suppression is likely to occur for a cavity depth as small as d/D<5%. This indicates how small the cavity depth should be to alleviate the resonance of diametral acoustic modes. The trend discussed above seems to be independent of the cavity length or the cavity free shear layer mode.

5.2 Effect of cavity depth on acoustic mode shapes and particle velocity distributions

As mentioned earlier, the radial component of the acoustic particle velocity *at the cavity free shear layer* is the acoustic parameter that affects the level of excitation. The maximum values of this radial component are shown in fig. 8 for the first three diametral modes. As discussed in section 3, the data in fig. 8 were extracted from the simulation of the acoustic modes (see fig. 9 as an example), whereby the maximum particle velocity for a particular mode is actually the average value along the cavity length at the azimuthal orientation corresponding to the maximum particle velocity, see fig. 9. The presented amplitudes correspond to a maximum acoustic pressure of one Pascal at the centre of the cavity floor.

For all three diametral acoustic modes, it is evident from fig 8 that the amplitude of the radial particle velocity along the cavity mouth increases with the cavity depth. As an example, the particle velocity of the first mode of d/D=4/12 is almost three times that corresponding to d/D=1/12. However, this ratio is much smaller than the measured increase in the acoustic pressure level as shown in fig. 7. This is because of the mutual enhancement mechanism between the vorticity-based excitation power and the acoustic particle velocity. Any increase in the vorticity-based sound power enhances the resonant sound field and therefore increases the particle velocity amplitude which, in turn, enhances the vorticity-based sound power. This cycle of events continues until the system reaches a saturation limit due to nonlinearity.

Referring back to fig. 8, the change of the acoustic particle velocity amplitude is not linear with the cavity depth and the rate of change is not the same for the different diametral acoustic modes. To clarify these features, the contour plots of the radial component of the particle velocity for the first three diametral modes are depicted in fig. 9. The contours are at cross section A-A of fig.2. The darkest and brightest areas represent the maximum amplitudes and are out of phase. The plots show that the areas with maximum radial particle velocity become closer to the cavity floor as the diametral mode number increases. This is why the order of the diametral modes *according to which has the higher radial particle velocity* changes with the cavity depth. For example, the third diametral mode has the highest value of the radial particle velocity for d/D=1/12 while it has the lowest value for d/D=4/12. Also, it seems that the maximum value of the particle velocity radial component for the third mode would occur close to d/D=3/12.

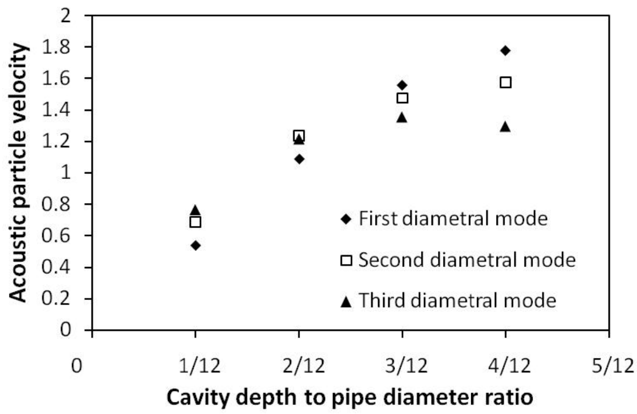

Figure 8: *Maximum radial acoustic particle velocity for different d/D ratios*

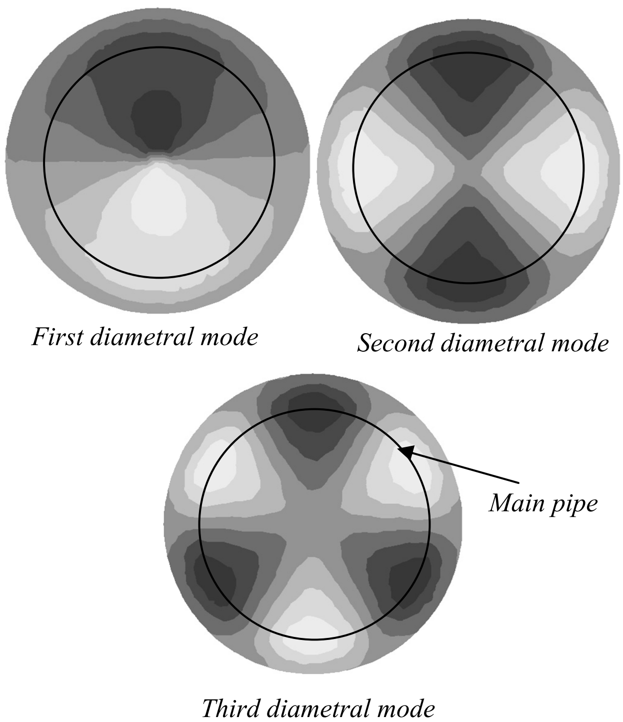

Figure 9: *Contour plots of radial particle velocity (d/D=2/12, L/D=0.17)*

5.3 Effect of cavity depth on mode selectivity

This section addresses the phenomenon of diametral mode selectivity for acoustic resonance when the cavity depth ratio (d/D) is altered. Figures 10(a) & (b) show the dominant acoustic modes over the tested flow velocity range for two cavities of equal length (L/D = 0.17), but different depths (d/D=1/12 & d/D=4/12), respectively. These figures, combined with fig. 5 which is for an equally long cavity but different depth (d/D=2/12), illustrate the phenomenon of susceptibility of different acoustic modes to excitation by various shear layer modes. They also illustrate the dependence of this phenomenon on the cavity depth ratio. It is noteworthy that all three cavities have the same length to ensure that the coincidence between the frequency of each shear layer mode and a particular acoustic mode occurs at approximately the same velocity. For d/D=1/12, the first diametral acoustic mode is not excited except over a very narrow velocity range. In this case, the higher order acoustic modes are more likely to be excited. On the other hand, for d/D=4/12, the lower order acoustic modes are the ones that are more likely to be excited. This indicates that for the deeper cavity (d/D=4/12), the lower order acoustic modes are more susceptible to acoustic resonance than the higher order modes. This trend is reversed for the shallower cavity (d/D=1/12).

Recalling fig. 8 again, the simulation results show that in the case of the deeper cavity (d/D=4/12), the acoustic particle velocity amplitude at the cavity mouth decreases with the increase of the acoustic mode order. However, the acoustic particle velocity is higher for the higher order acoustic modes in the case of the smaller depth cavity (d/D=1/12). These results clarify partially the phenomenon of mode selectivity of acoustic resonance and its dependence on the cavity depth. The results also underline the effect of changes in the diametral acoustic mode shapes on the aerodynamic excitation phenomenon.

6. CONCLUSIONS

The effect of cavity depth on the acoustic resonance mechanism of an axisymmetric shallow cavity in a duct has been investigated experimentally and numerically. It is shown that the level of aerodynamic excitation of the acoustic diametral modes increases as the ratio between the cavity depth and the pipe diameter is increased. The numerical simulations have shown that increasing the cavity depth increases the radial particle velocity amplitude at the cavity mouth, which enhances the vorticity-based acoustic power generation. The susceptibility of the different diametral acoustic modes to flow excitation is also dependent on the cavity depth. Higher order acoustic modes are shown to become more liable to shear layer excitation as the cavity is made shallower.

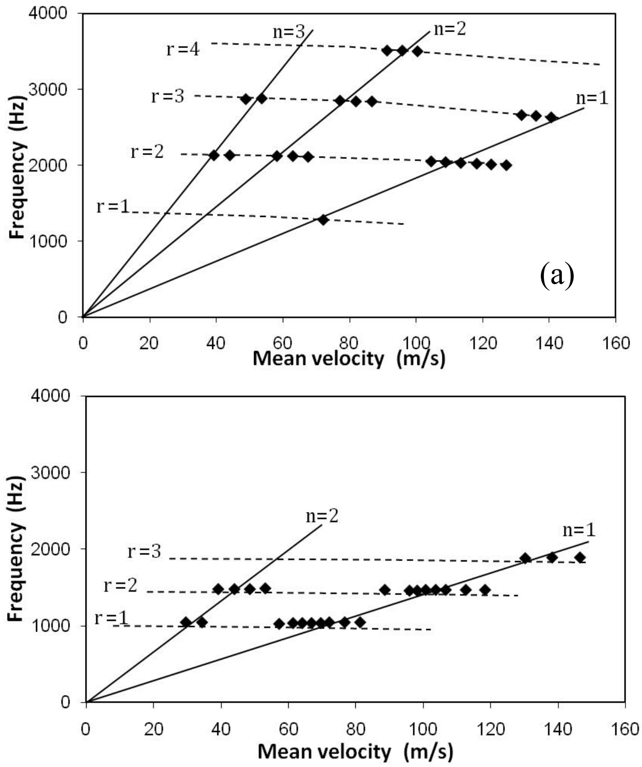

Figure 10: *Frequency of the dominant diametral acoustic modes a)d/D=1/12,L/D=0.17, b) d/D=4/12, L/D=0/17. (r: the acoustic mode number, n: the free shear lyaer mode number)*

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