Effect of Orifice Geometry on Helmholtz Resonator Excitation by Grazing Flow

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The characteristics of a Helmholtz resonator embedded under a turbulent boundary layer were experimentally investigated. Thirteen resonators were tested, each with different orifice geometries. The resonance frequency and pressure amplitude in the cavity were observed throughout the freestream velocity range. Orifice size, planform shape, and sidewall shape were all varied. For circular orifices, it was established that the response amplitude decreases with diameter, becoming negligible for diameters less than 5% of the boundary-layer thickness. The plan shape of the orifice affects both resonance frequency and maximum cavity pressure. Results are only roughly correlated by a Strouhal number containing the orifice length in the flow direction. The exact shape of the orifice sidewall also has an important effect on the resonator response. Orifices slanted toward the upstream flow have increased response, and those slanted downstream have negligible response. An orifice with rounded sidewalls both upstream and downstream has an unusually high response.

Nomenclature

c = speed of sound
f = resonance frequency from shear-layer excitation
f_o = resonance frequency, acoustic theory
H = cavity length
l' = effective orifice thickness
l_1 = secondary cavity length
L = orifice length in the flow direction
p = pressure
P_{rms} = cavity rms oscillating pressure
q = dynamic pressure
r_o = radius of equivalent circular orifice
r_1 = radius of secondary cavity
R = radius of cavity
S = area of orifice
t = thickness of orifice
u_* = friction velocity
V = freestream velocity
Vol = volume of resonator cavity
δ = boundary-layer thickness
ν = kinematic viscosity

I. Introduction

THE physical situation considered in this paper is a turbulent boundary layer with an orifice cut into the wall. The orifice diameter is somewhat smaller than the boundary-layer thickness, $1/3 < L/\delta < 1/60$, and it is backed by a relatively larger cavity to form a Helmholtz resonator. The arrangement is shown in Fig. 1. At resonance, a certain virtual mass of air located near the orifice undergoes large oscillations. The volume of air in the cavity is alternately compressed and expanded to produce a spring effect. Together, the mass and spring have a characteristic frequency, the Helmholtz frequency, determined by the speed of sound and the dimensions of the orifice and the cavity. The Helmholtz mode is a breathing mode with acoustic wavelength much longer than the cavity length. Higher-frequency standing-wave modes occur for wavelengths comparable to the cavity length.

Rockwell and Naudascher[1] reviewed flow-induced oscillations in cavities and placed Helmholtz resonators in the *fluid-resonant* group, a group where oscillations are influenced by resonant "wave" effects. In contrast, the *fluid-dynamic* group, consisting of simple cavities, has oscillations that arise from an inherent instability of the fluid flow. This later group has been studied extensively. It is important to note that the physical processes in the two groups are somewhat different.

Some of the first resonator tests with excitation by flow were by Harrington,[2] Ingard and Dean,[3] Philips,[4] and Panton and Miller.[5] De Metz and Farabee[6] made extensive measurements in an anachoic wind tunnel, and recently Erickson and Durgin[7] performed flow visualization tests. Another field of literature deals with the impedance of acoustic duct liners. In this case resonance frequencies are so low, or damping is so high, that they are mismatched to the fluid velocities and flow excitation does not generally occur. Notable exceptions are the work of Hersh and Walker,[8] who found that flow reso-

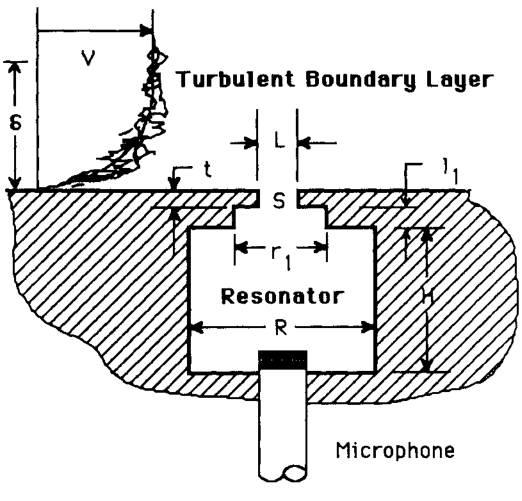

Fig. 1 Resonator geometry.

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nances corresponded to conditions where the orifice resistance became zero, and Goldman and Panton,[9] who also found negative resistances in nonlinear conditions. Although acoustic linings usually operate at much different values of $f_o \cdot L/V$ than the present experiments, some trends established here may be relevant to acoustic linings.

The general physical picture of flow-induced oscillations in a Helmholtz resonator is that the shear layer at the orifice produces eddies that grow as they are convected across the orifice gap. If the growth rate and freestream velocity, or more precisely the convection velocity, are the proper values, the eddy grows to fill the gap. In doing so the eddy causes a large compression in the cavity. Subsequently the compressed fluid ejects the eddy into the flow and a new eddy begins to grow to take the place of the previous one. An alternative idea,[5] that the turbulent eddies within the boundary layer itself excited the resonator, does not seem to be true.

Many previous results have shown that the frequency for Helmholtz resonance is roughly correlated on a "Strouhal" number, $f \cdot L/V$. For example, De Metz and Farabee[6] give $f \cdot L/V = 0.2$ for both slot-like and circular openings in the range $1/250 < L/\delta < 1/17$, but they note a rapid increase in this number for $L/\delta > 0.5$. The correlation of cavity pressures is an open question, however, cavity rms pressures are usually about one dynamic pressure of the flow.

The main objective of this research is to investigate the effect of orifice shape and size on the tuning of the boundary layer and the Helmholtz resonator, specifically to find the frequency range of tuning and to quantify the strength of the oscillations. The work falls into three parts: different orifice sizes ($1/60 < L/\delta < 1/3$), different orifice plan shapes, and different orifice wall shapes. All types are tested experimentally in a low-speed wind tunnel.

II. Experimental Arrangement

The resonators were embedded in the wall of an open-return wind tunnel with a 71.1 × 101.6 cm (28 × 40 in.) cross section. A continuously variable fan gave the tunnel a speed range of 8.94–71.5 m/s (20–160 mph). Ten resonator orifices were located in a line spanwise across the tunnel wall at a location 1.22 m (4 ft) from the test section entrance. The orifices, placed 3.04 cm (1.2 in.) on centers, occupied the central 27.4 cm (10.8 in.) of the 101.6 cm (40 in.) wall. Cavities behind the orifices were usually 2.54 cm in diameter and 10.4 cm (4.1 in.) in length. However, in one set of tests the cavities were modified by adding metal inserts to reduce the volumes. Each cavity was independent from the others and contained a microphone to measure the strength of the excitation. While tests were being conducted on one resonator, the orifices of all adjacent cavities were plugged. This avoids interactions between resonators that are known to occur.[10]

The test section was lengthened to 2.74 m (9 ft) so that the wall boundary layers could develop to a mature state, $Re_\theta \sim 6000$ at 26.8 m/s (60 mph). A rectangular strip, located 15.2 cm (6 in.) downstream from the entrance, served as a boundary-layer trip. In previous research[10] boundary-layer velocity measurements were made with a dual-beam-scatter LDV system of TSI equipment. Table 1 lists the boundary-layer properties as a function of tunnel speed. At the test location the boundary-layer properties are relatively constant with tunnel speed.

A typical test consisted of recording the cavity microphone rms pressure and the peak frequency, as determined by a spectrum analyzer, for a series of airspeeds from about 9.14 m/s (30 mph) to the maximum of 71.5 m/s (160 mph). Each different orifice is denoted by a number, one through ten, as shown in the list of resonator characteristics given in Table 2. Plan and cross-sectional side views of the orifices are shown in Fig. 2. The first three resonators give an insight into the effect of plan shape variations. Orifice number one is a straight-walled circular orifice. Number two is a long slot aligned with the flow, but having the same area as number one. Number three is the same type of slot, except across the flow. One should note that these resonators have identical acoustic properties. However, the orifice length in the flow direction L is different for each.

The effect of sidewall shape motivated the design of orifices four, five, and six. Numbers four and five were formed by a circular reamer cutting at a 45-deg angle. Four has an elliptical shape but the same cross-sectional area as number one. Number five is the same as four, except slightly larger. By reversing the orifice plate, the orientation of the axis with respect to the flow could be reversed. For example, "#5Dn" means the axis faces downstream, as depicted in Fig. 2. Orifice number six is a circular orifice with rounded sidewalls (the radius equal to half the orifice thickness). This slight modification gave very interesting results.

The remaining orifices, numbers seven through ten, have decreasing diameters and are all circular with straight sidewalls of various thicknesses. The "standard" cavity backed these orifices. As one can see in Table 2, these resonators have decreasing L, so the wind-tunnel velocity at which Helmholtz resonance occurred became very low. In fact, it turned out that in many cases the first measurable resonance was at a higher cavity mode. In a second series of tests, numbers 7A, 8A, and 9A, the resonator cavity volume was reduced so that the product $f_o \cdot L$ was almost constant. This was done so that the values of the parameter $V/(L \cdot f_o)$ for all of these different orifices would occur at the same airspeed and hence have the same boundary-layer characteristics.

Table 1

V, m/s (ft/s)	δ, cm (in.)	θ, cm (in.)	V/u_*
8.93(29.3)	2.95(1.16)	0.330(0.130)	23.3
17.7(58.2)	2.90(1.14)	0.312(0.123)	25.0
26.2(86.0)	2.90(1.14)	0.314(0.124)	26.1
35.7(117)	2.73(1.08)	0.305(0.120)	26.1
44.8(147)	2.59(1.02)	0.272(0.111)	27.2
60.0(197)	2.73(1.08)	0.278(0.113)	27.7
70.1(230)	2.73(1.08)	0.273(0.108)	27.9

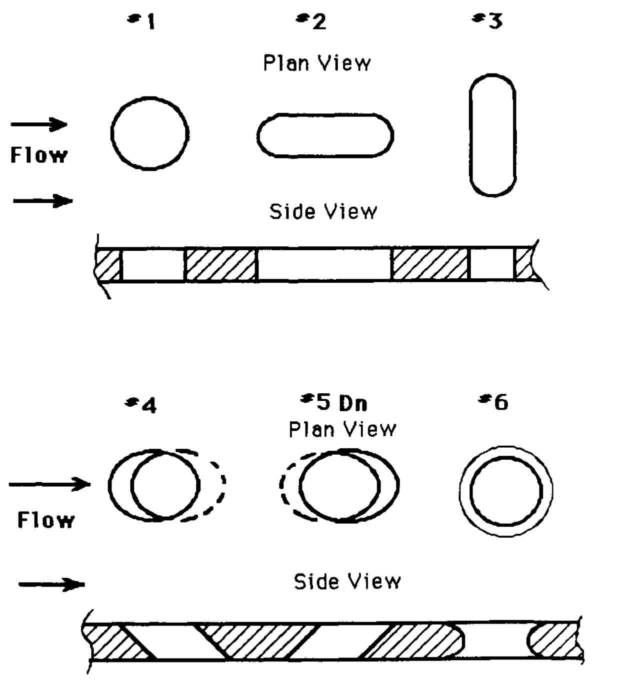

Fig. 2 Orifice geometry.

Table 2 gives the theoretical Helmholtz frequency for acoustic excitation calculated by the following formula:[11]

$$2\pi f_o = c\sqrt{\frac{S}{(l' \; Vol + H^2 S/3)}}$$

This is a slight refinement (see also Ref. 12) of the classical formula that accounts for the cavity length. The effective orifice length was calculated using Rayleigh's outside end-correction together with Ingard's[13] inside end-correction. From the preceding equation one can see that the resonator geometry, together with the speed of sound, determines the acoustic Helmholtz frequency. Thus, f_o is a convenient scale for nondimensionalizing variables. The value of f_o in Table 2 is for a standard temperature of 58.9°F. During tests, f_o was about 10 Hz higher.

III. Discussion and Results

In all of the tests, attention was directed to the resonator cavity microphone signals for a sequence of runs where the freestream airspeed was varied. Figure 3 is a plot of the rms resonator pressure referenced to the dynamic pressure q. The tunnel speed V is normalized by $L \cdot f_o$, the reciprocal Strouhal number based on f_o. (Plotting response in this way is preferred since a plot of p_{rms}/q vs $V/(L \cdot f)$ involves two dependent variables, p_{rms} and f). At about $V/(L \cdot f_o) = 2.8$ (35 mph), the boundary layer begins to excite the resonator. The cavity-pressure oscillation peaks out at $p/q = 0.8$ when the airspeed is about $V/(L \cdot f_o) = 3.7$ (55 mph). At higher speeds the resonator detunes and the response falls. Further increases in speed bring another excitation, this being at the first standing-wave mode, starting about $V/(L \cdot f_o) = 9$ (120) mph with the response rising to $p_{rms}/q = 0.3$ at the maximum tunnel speed of $V/(L \cdot f_o) = 12$ (157 mph). The response value of nearly one dynamic pressure at $V/(L \cdot f_o) \sim 4$ is roughly in agreement with many previous cavity and resonator tests. One should note that the peak in Fig. 3 is not the maximum cavity pressure because the dynamic pressure, used to normalize the graph, increases as the velocity squared. The second increase in response at $V/(L \cdot f_o) \sim 12$, the first standing-wave mode becoming active, has a higher absolute cavity pressure (150 db) than that of the first peak (140 db).

The resonator frequency is plotted in Fig. 4. When the response first begins, the frequency is about $f/f_o = 0.925$ (518 Hz), but it slowly moves upward to about $f/f_o = 1.075$ (602 Hz). For comparison, the nominal Helmholtz frequency for acoustic excitation of these resonators is 560 Hz at the test temperature. The frequency of response is apparently fixed by the fluid flow processes at the shear layer; i.e., the "driving" frequency has a sharp peak that is a slow function of velocity. Resonator tests with acoustic excitation show a broad range of frequency where the response is high. This same behavior

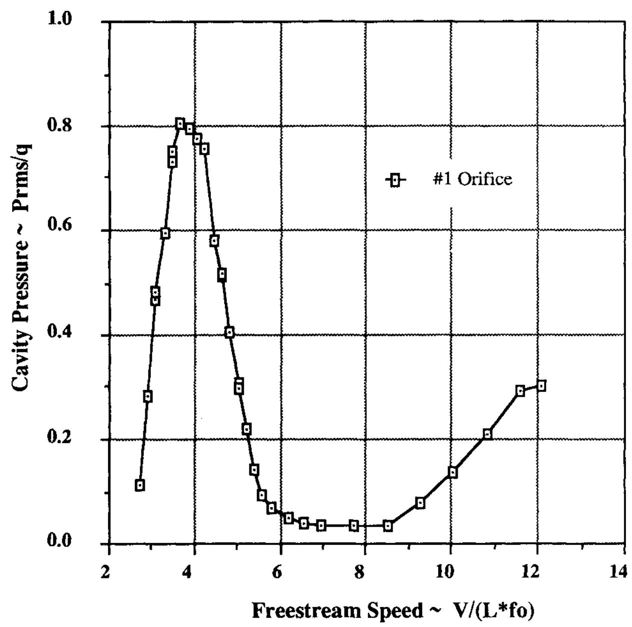

Fig. 3 Excitation amplitude of a resonator with a circular orifice.

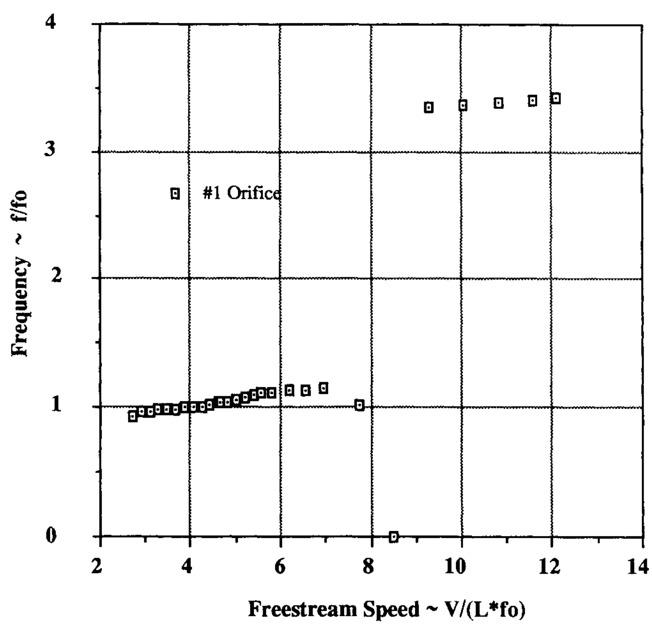

Fig. 4 Excitation frequency of a resonator with a circular orifice.

Table 2 Physical dimensions and Helmholtz frequency of resonators

Resonator number	r_o, mm	t, mm	R, mm	r_1 mm	l_1, mm	H, mm	l', mm	S, cm^2	Vol, cm^3	L, mm	f_o, Hz
1	5.156	3.048	12.700	0.000	0.000	106.7	9.599	0.8352	54.06	10.31	542
2	5.156	3.048	12.700	0.000	0.000	106.7	9.599	0.8352	54.06	18.54	542
3	5.156	3.048	12.700	0.000	0.000	106.7	9.599	0.8352	54.06	4.76	542
4	5.156	3.048	12.700	0.000	0.000	106.7	9.599	0.8352	54.06	12.32	542
5	6.121	3.048	12.700	0.000	0.000	106.7	10.336	1.1772	54.06	14.58	587
6	5.118	3.048	12.700	0.000	0.000	106.7	9.567	0.8229	54.06	11.76	540
7	2.578	0.762	12.700	4.699	2.286	106.7	3.651	0.2088	54.23	5.16	471
7A	2.578	0.762	6.350	4.699	2.286	50.8	3.651	0.2088	6.61	5.16	1208
8	1.588	0.254	12.700	4.699	2.794	106.7	2.385	0.0792	54.27	3.18	382
8A	1.588	0.254	3.810	4.699	2.794	38.1	2.385	0.0792	1.95	3.18	1657
9	0.794	0.254	12.700	4.699	2.794	106.7	1.461	0.0198	54.27	1.59	259
9A	0.794	0.254	3.810	4.699	2.794	2.5	1.428	0.0198	0.33	1.59	3498
10	0.397	0.254	6.350	4.699	2.794	106.7	0.893	0.0049	13.73	0.79	321

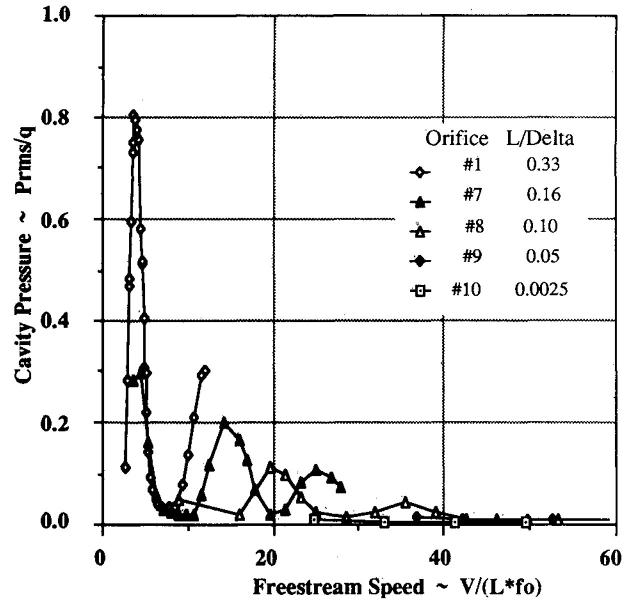

Fig. 5 Excitation amplitude: orifice diameter effects.

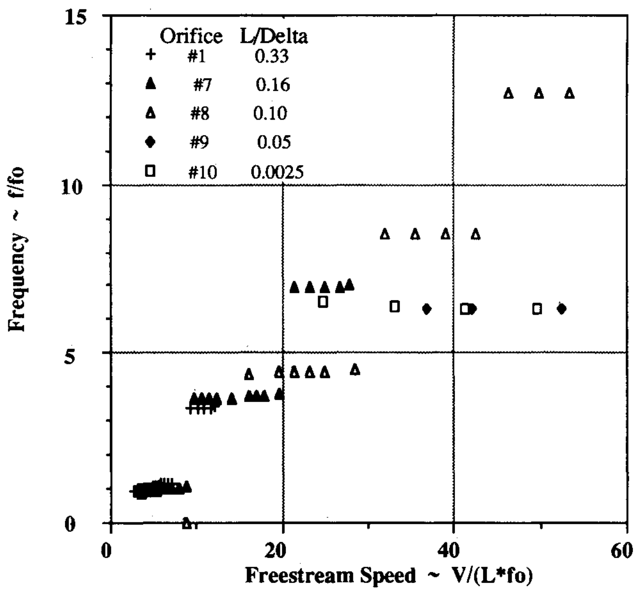

Fig. 6 Excitation frequency: orifice diameter effects.

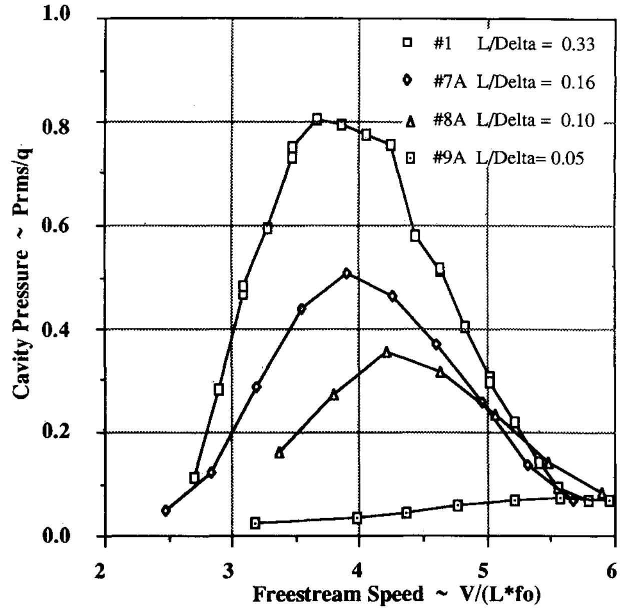

Fig. 7 Excitation amplitude: orifice diameter effects with $L \cdot f_o$ constant.

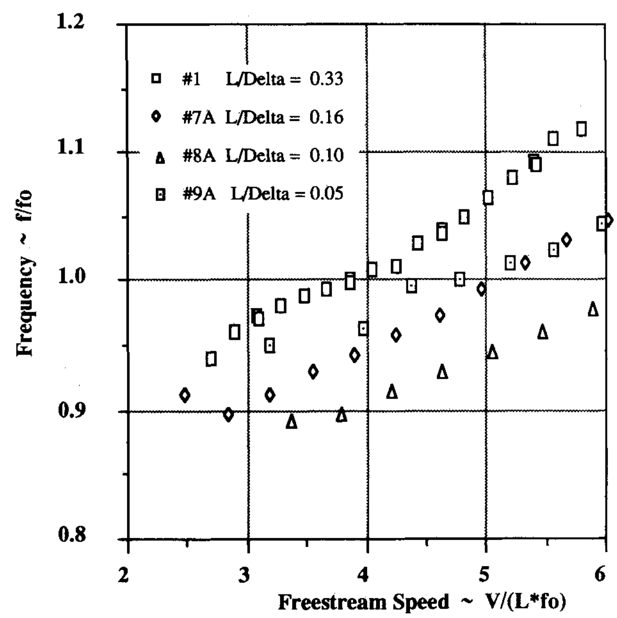

Fig. 8 Excitation frequency: orifice diameter effects with $L \cdot f_o$ constant.

occurs again at higher airspeeds for the first standing-wave mode; it moves from $f/f_o = 3.3$ (1840 Hz) to $f/f_o = 3.35$ (1884 Hz).

The first two series of tests were to determine the effects of different-sized circular orifices. Figures 5 and 6 show response data for all the circular orifices backed by the "large" cavities. Only numbers one and seven were found to oscillate at the Helmholtz frequency. The reason is that the other resonators have such low f_o values that $V/(L \cdot f_o) = 4$ occurs at a very low velocity. When the velocity is low, the dynamic pressure is very small and ambient acoustic noise masks the excitation. Figure 5 reveals that the first and second standing-wave frequencies are excited to a lesser fraction of q as the orifice diameter decreases or as the tunnel speed increases. In fact, orifice number ten was never significantly excited in tests as high as $V/(L \cdot f_o) = 150$. The higher standing-wave modes in Fig. 6 do not in principle have the same relation to f_o for each different resonator.

In a second series of tests, the cavities behind orifices numbers seven, eight, and nine were changed to increase f_o so that $L \cdot f_o$ was nearly constant. Hence, a value $V/(L \cdot f_o) = 4$, say, occurs at the same V for all resonators. This means that at resonance, all resonators have the same driving conditions, i.e., the same q and the same boundary-layer properties. Only the orifice diameters (and cavities) are different for each test. The results, shown in Fig. 7, reveal a systematic decrease in peak pressure response. This may be viewed as an L/δ effect from the boundary layer. (It is possible that other properties of the resonator cavities are also important. To test this, one should test cavities with the same volume but different shapes.) For $L/\delta = 0.10$ the amplitude is reduced by a half, and for $L/\delta = 0.05$ the response is practically zero. Because the smallest diameter is still about 100 viscous length scales (ν/u_*) of the boundary layer, it is unlikely that the decreased response is a viscous effect. It is conjectured that the decrease in peak response is from the turbulent eddy motions within the boundary layer interfering with the eddy growth in the shear layer at the orifice.

Figure 8 shows that the resonance frequencies increase at roughly the same rate for all resonators in the circular orifice group. The differences in levels of the f/f_o curves in Fig. 8 is probably not significant. The formula to predict f_o is not that accurate when the end corrections are modified by an imposed grazing flow.

The effect of orifice plan shape was investigated using three orifices with the same area and thickness. Recall that orifice number two is the slot aligned with the flow direction. It has a reduced peak response level, as seen in Fig. 9, and a very steep increase in frequency with freestream speed,, as seen in Fig. 10. The slot aligned across the flow (number three) has the usual level of peak pressure excitation, as seen in Fig. 9, but at 20% increase in the tunnel speed parameter $V/(f_o \cdot L)$. Also, Fig. 10 shows it has a lower than nominal increase in resonance frequency with increasing flow speed. Taken together, these curves show that the concept of correlating resonator response with a Strouhal number containing L as the flow-direction orifice dimension is only a rough guide. With the limited information obtained in these tests (note that L/δ is different for each orifice), it is not possible to give a physical rationale for these results.

The last set of curves, Figs. 11 and 12, deals with the effects of orifice wall shape. Orifices drilled with the axis facing upstream, i.e., holes tending to readily scoop flow into the cavity, are numbers four and five. They both show a much higher peak pressure than the circular orifice. Nevertheless, all peak at approximately the same speed. On the other hand, when the axes are directed downstream, #4Dn and #5Dn, the response is virtually vanished; something less than $0.2q$. Obviously, the orifice thickness must play a role here, because as the thickness is reduced to zero, the "upstream" and "downstream" axis configurations would be identical.

Orifice number six had an even larger response. In Fig. 11 the peak pressure response is 50% higher than for the straight-walled circular orifice. This orifice has smoothly rounded sidewalls. They probably aid the motion of the flow into the cavity, as well as the return flow out of the cavity. From another point of view, the separation and reattachment points on the rounded sidewalls could move to more favorable positions on the rounded sidewalls during an oscillation cycle. Sharp corners, on the other hand, would pin the

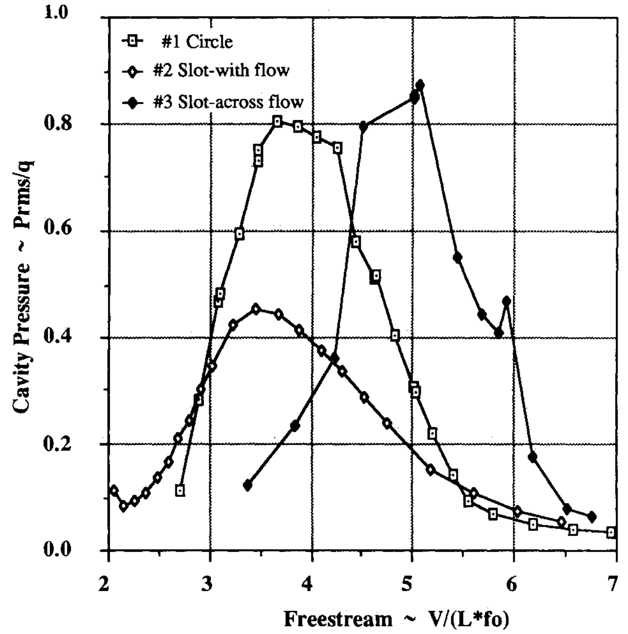

Fig. 9 Excitation amplitude: orifice plan shape effects.

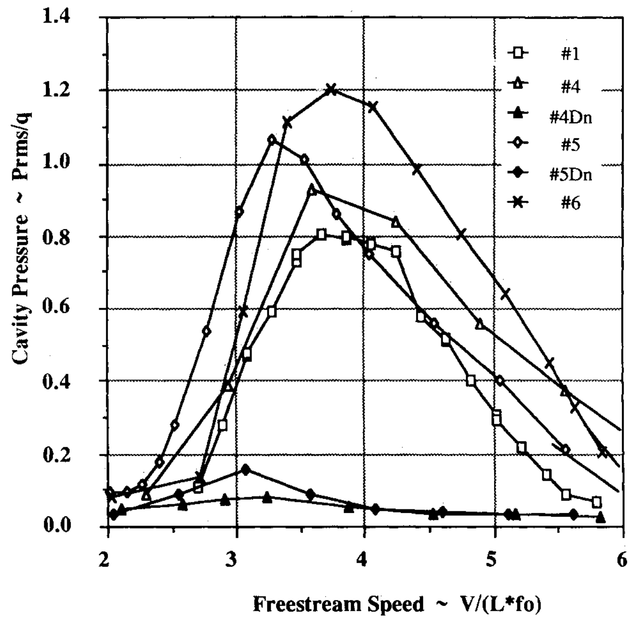

Fig. 11 Excitation amplitude: orifice wall shape effects.

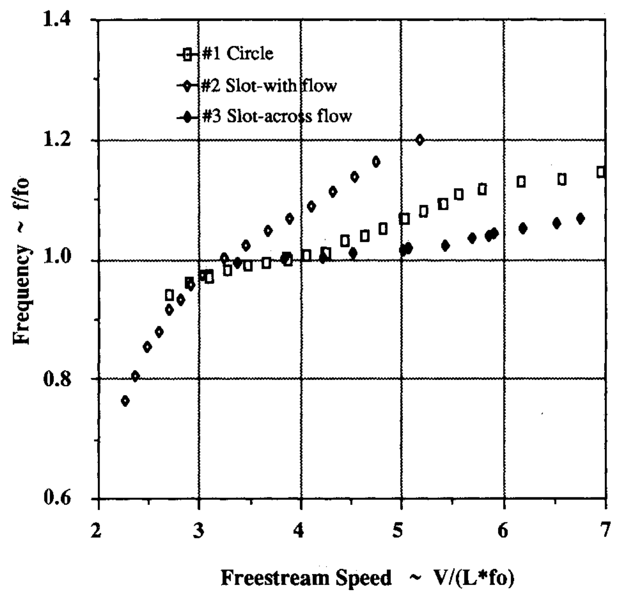

Fig. 10 Excitation frequency: orifice plan shape effects.

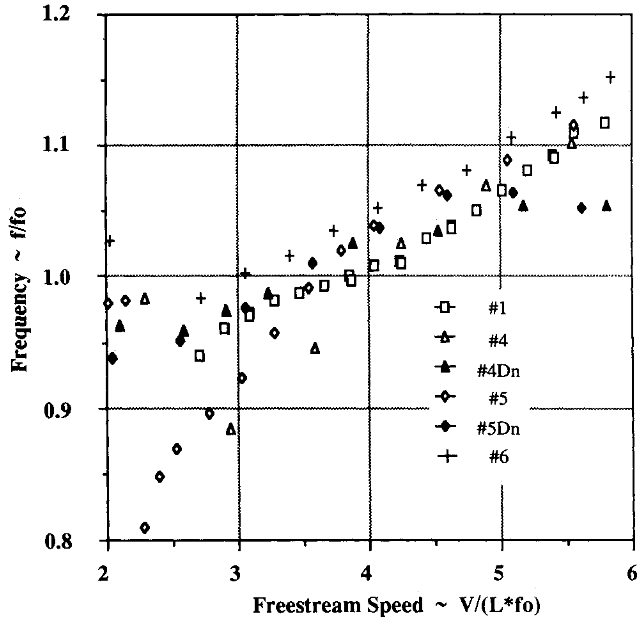

Fig. 12 Excitation frequency: orifice wall shape effects.

separation point. Here again, thickness must play an important role as in the limit of zero thickness the orifice would be the same as a straight-walled orifice.

IV. Summary of Major Results

When an orifice is approximately the same size as the boundary layer above it, the response of a resonator is greatly influenced by the size and shape of the orifice. With regard to the size of circular orifices, it is definitely established that as L/δ decreases, the peak cavity response p_{rms}/q decreases, becoming negligible for $L/\delta = 0.05$. The mechanism for this decrease is conjectured to be turbulent boundary-layer eddies interfering with the eddy growth in the orifice shear layer. In accordance with previous experiments, the peak response occurs when the freestream velocity is $V/(L \cdot f_o) = 4$ for the Helmholtz mode. The response level for higher modes is a smaller fraction of the dynamic pressure, the higher the mode. The plan shape of the orifice affects both the maximum p_{rms}/q and the value of $V/(L \cdot f_o)$ at which it occurs. Results are only roughly correlated by using the flow-direction length in this parameter. This is particularly true for a high-aspect ratio orifice that is aligned with the flow. The exact shape of the orifice sidewall can also have a drastic effect on the resonator response. Orifices that aid the inflow of boundary-layer fluid have increased response, and those that inhibit inflow have negligible response. An orifice with rounded sidewalls both upstream and downstream has an unusually high response.

References

[1]Rockwell, D. and Naudascher, E., "Review—Self-Sustaning Oscillations of Flow Past Cavities," *Transactions of ASME, Journal of Fluids Engineering*, Vol. 100, 1978, p. 152.

[2]Harrington, M. C., "Excitation of Cavity Resonances by Air Flow," Abstract, Meeting of American Physical Society, Division of Fluid Dynamics, Bulletin of the American Physical Society, American Institute of Physics, New York, 1957.

[3]Ingard, U. and Dean, L. W., "Excitation of Acoustic Resonators by Flow," *Second Symposium on Naval Hydrodynamics*, Office of Naval Research, Washington, D.C., 1958, p. 137.

[4]Phillips, B., "Effects of High Amplitude and Mean Flow on a Helmholtz Resonator," NASA TM-X-1582, 1968.

[5]Panton, R. L. and Miller, J. M., "Excitation of a Helmholtz Resonator by a Turbulent Boundary Layer," *Journal of the Acoustical Society of America*, Vol. 58, No. 4, 1975, p. 800.

[6]De Metz, F. C. and Farabee, T. M., "Laminar and Turbulent Shear Flow Induced Cavity Resonances," AIAA Paper 77-1293, Oct. 1977.

[7]Erickson, D. D. and Durgin, W. W., "Tone Generation by Flow Past Deep Wall Cavities," AIAA Paper 87-0167, Jan. 1987.

[8]Hersh, A. S. and Walker, B. "The Acoustic Behavior of Helmholtz Resonators Exposed to High Speed Flows," AIAA Paper 76-536, 1976.

[9]Goldman, A. L. and Panton, R. L., "Acoustic Impedance of an Orifice Under a Turbulent Boundary Layer," *Journal of the Acoustical Society of America*, Vol. 60, No. 6, 1976, p. 1397.

[10]Flynn, K. P., Panton, R. L., and Bogard D. G. "The Effect of a Row of Helmholtz Resonators on the Turbulence of a Boundary Layer," AIAA Paper 89-0961, 1989.

[11]Panton, R. L. and Miller, J. M., "Resonant Frequencies of Cylindrical Helmholtz Resonators, *Journal of the Acoustical Society of America*, Vol. 57, No. 6, 1975, p. 1533.

[12]Monkowitz, P. A. and Nguyen-Vo, N.-M. "The Response of Helmholtz Resonators to External Excitation. Part 1. Single Resonators," *Journal of Fluid Mechanics*, Vol. 151, 1985, p. 477.

[13]Ingard, U., "On the Theory and Design of Acoustic Resonators," *Journal of the Acoustical Society of America*, Vol. 25, No. 6, 1953, p. 1037.