Measurements of Sound Radiation from Cavities at Subsonic Speeds

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To better understand the physical mechanisms responsible for noise generated by flow over large cavities, a series of measurements of far-field sound pressure level, fluctuating surface pressure, and drag coefficient was made. An examination of the resultant data shows that two theoretical models are needed for this range of dimensions. The shallow cavity (width-to-depth ratio larger than 1.0) can be approximated by a dipole located near the downstream edge of the cavity, and the deep cavity (ratio less than 1.0) can be approximated by a dipole located near the downstream edge with the superimposed effects of the upstream edge of the cavity.

Introduction

TO gain a better understanding of the physical mechanisms responsible for the noise generated by landing gear cavities with dimensions similar to those used on commercial aircraft, an investigation of the acoustic far-field and fluctuating surface pressures of cavities has been carried out in the Ames 7- × 10-ft (2.1- × 3.0-m) wind tunnel.

Many investigators have measured the characteristics of acoustic radiation from cavities since the original work of Karamcheti.[1,2] Because of the interest in bomb-bay flows, most of the work has been concentrated on high freestream velocities. Figure 1 shows the range of cavities and Mach numbers covered. However, little work has been done with width-to-depth ratios typical of commercial aircraft wheel wells. Therefore, our experiment covers the width-to-depth ratios of cavities ranging from 0.4 to 2.0 and freestream velocities ranging from 39.6 m/sec (130 ft/sec) to 93.3 m/sec (306 ft/sec). For each configuration and velocity, far-field noise spectra, pressure fluctuations near cavity edges, and drag coefficient were measured. Results were analyzed to determine the flow characteristics in the cavity, and the velocity dependence and directivity of the acoustic radiation.

Nature of the Problem and Background

Pressure fluctuations in the vicinity of cut-outs and cavities are of considerable interest not only because of structural effects, but because of sound generation due to the cavity. This cavity noise has the following features (see Fig. 2 for nomenclature):

1) For a certian range of cavity geometry, called a shallow cavity, where cavity width is the important parameter, the pressure fluctuations have random characteristics. The mechanism of cavity oscillation in this range is assumed to be one of longitudinal mode or amplification of disturbances through the shear layer.

2) For another range of cavity geometry, called a deep cavity, where cavity depth is the important parameter, periodic pressure fluctuations are generated. This mechanism of cavity oscillation is assumed to be one of depth mode.

3) The frequency of the periodic pressure fluctuations increases with the velocity up to a certain velocity where the oscillation jumps to a higher mode.

4) There exists minimum width or velocity, below which no sound is generated.

5) The radiation field exhibits directional characteristics.

6) The downstream edge of the cavity is an important area in generating noise.

Based on the different characteristics of the flowfield and acoustic field (to be shown in the following sections), cavities can be classified as either deep or shallow. From previous experiments and our results, the division between the shallow and deep cavities occurs at the width-to-depth ratio R of approximately 1.0. That is, when R is greater than 1.0, the cavity is considered a shallow cavity; for R being less than 1.0, the cavity is considered a deep cavity.

For shallow cavities, Karamcheti[1,2] hypothesized that the inherent instability of the separated shear layer over the cavity, shed from the upstream edge of the cavity, plays the dominant role in the sound generation. The reason for that assumption is the existence of a minimum width or velocity for the onset of discrete frequency oscillation of pressure fluctuations for a given condition. He also assumed that the frequency that is amplified most through the shear layer is the one observed. Plumblee et al.[3] examined this model and wondered why the cavity response was not merely the amplification of a band of frequencies rather than a single frequency within this band. Consequently, they hypothesized that the mechanism of the oscillations in cavities can be described by determining the characteristic response of a rectangular enclosure. They calculated the acoustic modes of a five-sided rectangular enclosure of inifinite impedance (i.e. rigid walls) and a sixth surface with a finite complex impedance. From these calculations, they concluded that the resonant response is the depth mode for deep cavities and longitudinal mode for shallow cavities. They also concluded

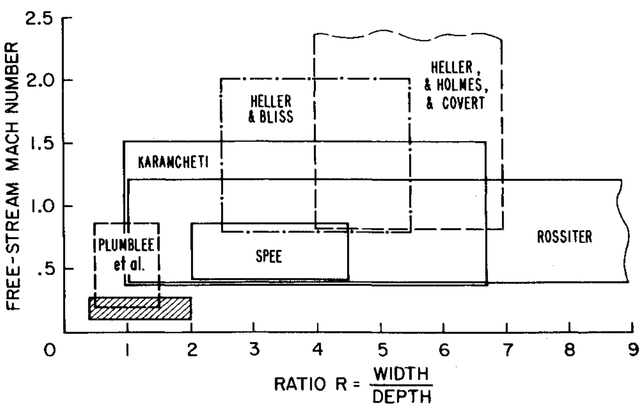

Fig. 1 Experimental work done in cavity noise (shaded area: range of cavities for commercial aircraft wheel wells and also range for our experiment).

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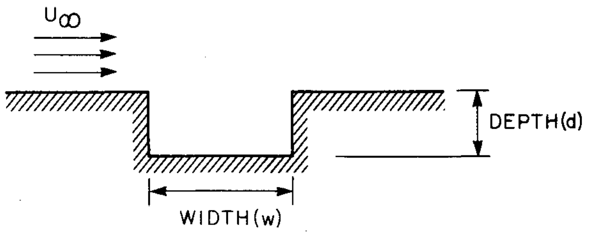


Fig. 2 Cavity geometry.

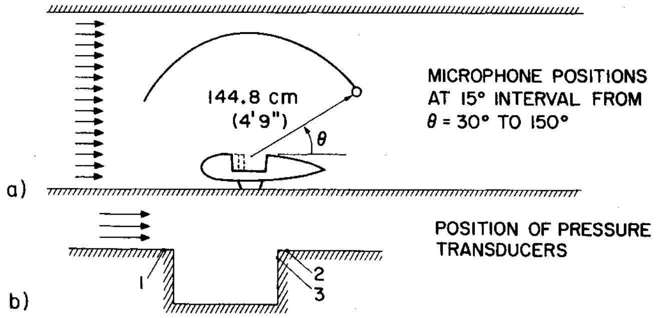


Fig. 3 Schematic layout of test section and position of pressure transducers.

that the periodic pressure fluctuations in cavities are due to an acoustic resonance excited by the unsteadiness in the turbulent boundary layer approaching the cavity. However, Karamcheti[1,2] showed that the periodic pressure fluctuations are present when the boundary layer is laminar. Therefore, Rossiter[4] hypothesized that the forcing function is related to the flow over the cavity rather than the boundary layer at the upstream edge of the cavity. He assumed that periodic vortices are shed at the upstream edge in sympathy with the pressure oscillation produced by the interaction of the vortices with the downstream edge. Using this model, Rossiter[4] derived a formula for the oscillating frequency with two empirically determined constants. This formula was extensively correlated with experimental results by Heller and others.[5,6] After observing wind-tunnel experiments, Heller et al.[5,6] postulated that the shear layer interacts with the downstream edge to produce a wave that reaches the upstream edge, thereby triggering a disturbance in the shear layer. Furthermore, they showed that an essential feature of the phenomena is the periodic addition and removal of mass around the downstream edge of the cavity, which can be modeled with an oscillating piston.

Although the feedback mechanism as suggested by Rossiter[4] and extensively used by Heller et al.[5,6] estimated possible excitation frequencies, it did not predict which one of these frequencies would actually be amplified. Selection of the excited frequency was assumed to be a function of the stability characteristics of the shear layer over the cavity. The aspect of the instability characteristics of the shear layer had not been fully developed until Woolley and Karamcheti[8,9] pursued the acoustic problem in transonic wind tunnels with ventilated walls. They carried out calculation of the instability characteristics for an almost parallel flow to explain the sound generation and its physical features, and from these features the frequency of the most amplified disturbance and the amplification it receives may be determined. To better analyze the instability characteristics, Sarohia[10] carried out detailed measurement of the shear layer. He concluded that the mode of cavity oscillation can be predicted for a given cavity flow by simultaneously studying the phase and integrated amplification of various disturbance frequencies through the shear layer, then applying the mode relation.

Even though many experiments have been performed on cavity oscillations and noise, there have been only a few attempts to formulate a simple theoretical model for cavity

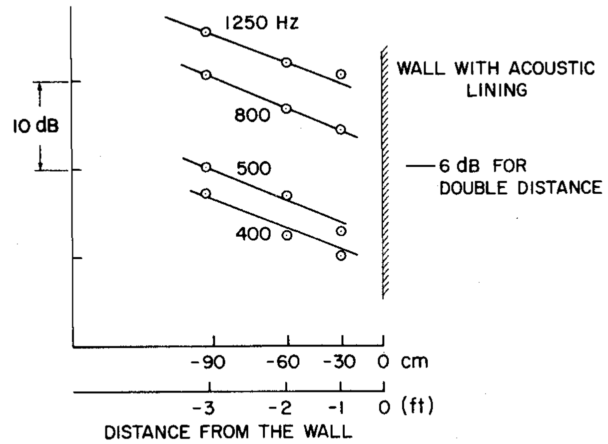


Fig. 4 Acoustic characteristics of test section with acoustic lining (from Ref. 12).

noise. Bilanin and Covert[11] modeled the dominant pressure fluctuations at the downstream edge as a single periodic acoustic monopole. However they did not experimentally consider the acoustic field. Therefore, in order to make a reasonable theoretical model of the cavity noise, we measured the acoustic field and pressure fluctuations on the surface of the cavity.

Details of the Experiment

Small-Scale Test

An NACA 0018 symmetric airfoil of 76.2 cm (2.5 ft) span length, 76.2 cm (2.5 ft) chord length, and 11.43 cm (5.5 in.) thick was mounted near the floor of the Ames 7×10-ft (2.1×3.0-m) wind tunnel. This airfoil has a two-dimensional cavity 7.62 cm (3 in.) deep and width variable from 15.24 cm (6 in.) to 3.05 cm (1.2 in.) by inserting blocks (Fig. 3). This results in width-to-depth ratios R from 2.0 to 0.4.

The test section walls were covered with an acoustic material to reduce reverberations. The acoustic lining was 7.6 cm (3.0 in.) deep Scottfelt 3-900. The acoustic environment was evaluated by measuring the noise from a low-frequency woofer and a midrange horn driver (see Fig. 4). Details of measurements can be found in Ref. 12. Measurements show that the sound pressure level for the frequencies of interest attenuates as in a freefield.

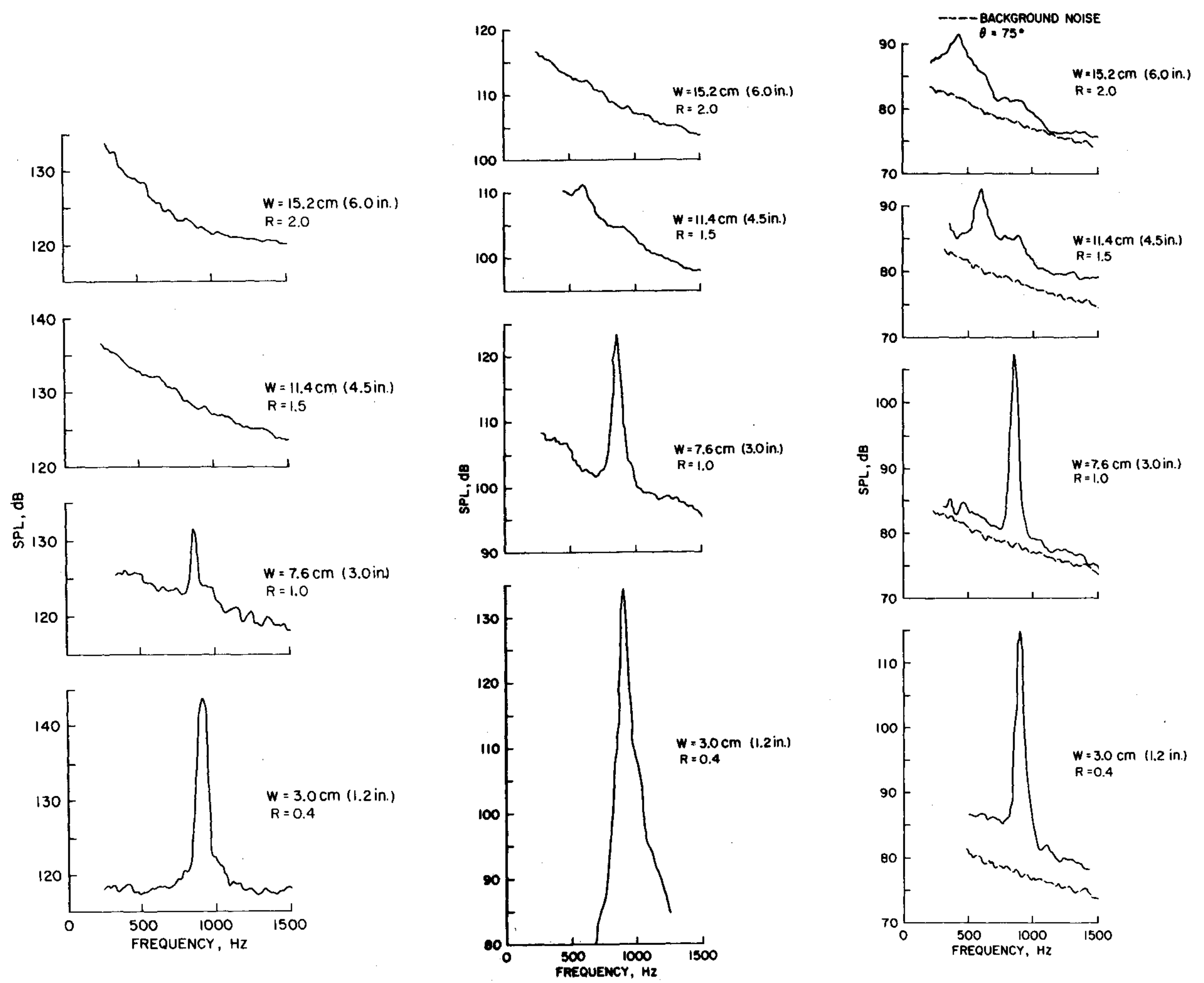
Noise measurements were taken with a microphone mounted vertically from the ceiling of the test section at angles ranging from $\theta = 30°$ to $150°$ at intervals of $15°$. The microphone leg was adjusted at each position to keep the distance from the microphone to the midpoint of the cavity at 145 cm (4 ft 9 in.) (see Fig. 3). Three BBN 0.25-cm (0.1-in.) pressure transducers were flush-mounted on the upstream and downstream edges of the cavity (one for the upstream edge and two for the downstream edge) (Fig. 3b). The majority of data was obtained with this small-scale model.

Large-Scale Test

Another NACA 0018 symmetric airfoil of 304.8 cm (10 ft) span, 304.8 cm (10 ft) chord, and 45.7 cm (1.5 ft) thickness was used. This airfoil has a cavity 30.5 cm (1 ft) deep and width variable from 61 cm (2 ft) to 12.2 cm (0.4 ft) by inserting blocks. There were several BBN 0.25-cm (0.1-in.) pressure transducers mounted flush on the cavity surface. Since the test section walls in this case were not covered with an acoustic material, this large-scale model was used only to determine the peak frequencies for the Strouhal number analysis and the drag coefficient.

Data Acquisition and Reduction

The measuring and recording equipment consisted of a 1.3-cm (0.5-in.) B&K condenser microphone (2619 preamplifier and 4133 microphone cartridge) with an ogive noise cone,



a) Downstream edge b) Upstream edge c) Microphone signal

Fig. 5 Frequency spectrum of pressure transducers and a microphone for various cavity widths [$U_\infty = 62.5$ m/sec (205 ft/sec), $d = 7.6$ cm (3.0 in.)].

BBN 0.25-cm (0.1-in.) pressure transducers, Newport 70 A preamplifier for the pressure transducers, Ampex FR 1300A tape recorder, Tektronix type 564 oscilloscope, microphone signal conditioner, and voltmeter. Signals from the test were processed with a SAICOR 52-C real-time spectrum analyzer and a SAICOR SAI-43A correlation and probability analyzer.

Experimental Results and Discussion

Far-Field and Surface Pressure Spectra

Sound and surface pressure spectra measurements for different cavity widths with constant depth are shown in Fig. 5 for a velocity of 62.5 m/sec (205 ft/sec). These variations are typical of those at other velocities. When the width w is larger that 11.4 cm ($R > 1.0$), the signal of the pressure transducer at the downstream edge of the cavity has a broadband spectrum, whereas the frequency spectrum becomes discrete for the width w less than 7.6 cm ($R < 1.0$). Results at the upstream edge show similar features. However, the microphone signal showed a definite discrete frequency for all widths at a velocity of 62.5 m/sec (205 ft/sec). This dominant frequency and its level increase as width decreases, where the dominant frequency varies from about 500 Hz for $w = 15.2$ cm ($R = 2.0$) to about 1000 Hz for $w = 3.0$ cm ($R = 0.4$); the microphone signal level for the dominant frequency varies from about 92 dB for $w = 15.2$ cm ($R = 2.0$) to about 115 dB for $w = 3.0$ cm ($R = 0.4$). All dominant frequencies are tabulated in Table 1. The cross correlation of pressure fluctuation signals from the two edges of the cavity shows that the downstream fluctuating pressures propagate upstream through the shear layer for both shallow and deep cavities (see Fig. 6), where the delay time τ_0 for the first peak corresponds to the traveling time of the fluctuating pressure signal from the downstream edge to the upstream edge. As in Fig. 6a, which is a typical curve for broadband signals, this delay time τ_0 is equal to the distance between the two pressure transducers divided by sound speed. However, in Fig. 6b, which is a typical curve for discrete frequency signals, the correlation curve has the form of a simple sine curve and the delay time τ_0 is not equal to the distance between the two pressure transducers divided by sound speed.

As shown in Fig. 7, for shallow cavities (see Figs. 7a, b) a certain frequency is amplified at the upstream edge or at the microphone even though there is no discrete frequency at the downstream edge, while for deep cavities (see Figs. 7c, d) a

Table 1 Dominant frequencies of a microphone signal for different widths and velocities [$d = 7.6$ cm (3.0 in.)]

WIDTH / FREE-STREAM SPEED	3.0 cm (1.2 in.)	7.6 cm (3.0 in.)	11.4 cm (4.5 in.)	15.2 cm (6.0 in.)
39.6 m/sec (130 ft/sec)	670 HZ	570 HZ	490 HZ	*
56.1 m/sec (184 ft/sec)	860	775	570	550
62.5 m/sec (205 ft/sec)	950	850	620	700

*Denotes no discrete frequency.

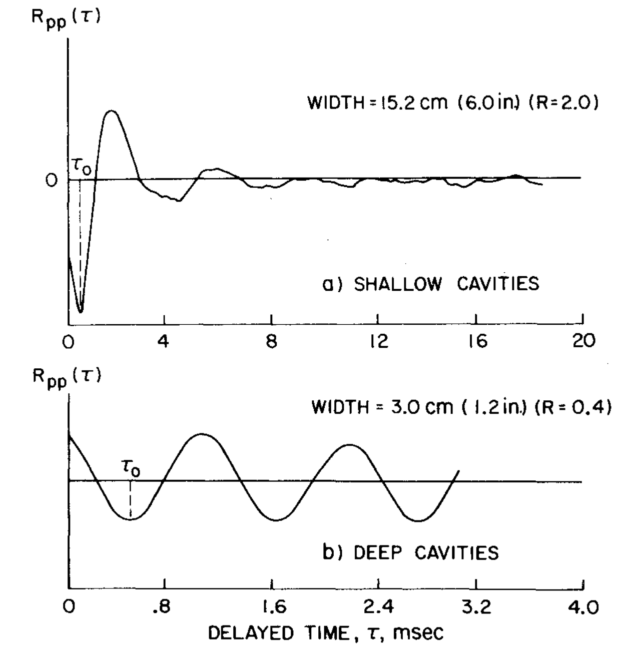


Fig. 6 Cross-correlation curve between signals of pressure transducers at upstream and downstream edges (downstream edge signal delayed [$U_\infty = 62.5$ m/sec (205 ft/sec), $d = 7.6$ cm (3.0 in.)].

discrete tone appears at both upstream and downstream edges, and also the tone is amplified at the upstream edge. The amplification of a certain frequency at the upstream edge can be explained by the analysis of Woolley and Karamcheti[8,9] using the instability characteristics of nonparallel flow where the dominant frequencies can be assumed to be the one most highly amplified through the shear layer. However, for deep cavities where dominant frequencies exist at both upstream and downstream edges, the dominant frequencies can be assumed to correspond to natural acoustic modes of the cavities as had been assumed by Plumblee et al.,[3] and our dominant frequencies for deep cavities are in reasonable agreement with the simple characteristic frequency calculations of the acoustic depth mode of Plumblee et al.[3]

The pressure fluctuations on the upper and side surfaces at the downstream edge for shallow cavities are shown in Fig. 8. The signals of the two pressure transducers are very similar and further examination shows them to be in phase. Unfortunately, we did not have the corresponding measurement for deep cavities. However, it is concluded from these results that the shear layer sheds from the upstream edge and is sufficiently thick that it covers both sides of the downstream edge at all times during the oscillation of the shear layer about the downstream edge. It also means that there is no cross flow between pressure transducers 1 and 2 over the downstream edge. This differs from the hypothesis in which a shear layer shed from the upstream edge changes its position between below and above the downstream edge. This phenomenon would require that the fluctuating pressures at the two positions be 180° out of phase, which our measurements do not show.

Strouhal Number

Since the dominant frequencies are assumed to be the one most highly amplified through the shear layer over the cavity, the width w is used as a characteristic length in the following nondimensional forms. Figure 9 shows the Strouhal number of the discrete frequency as a function of Reynolds number for purpose of estimating dominant frequencies in other cavities. In this figure, we limited the data from other references to width-to-depth ratios of less than 2.0. Except for low Reynolds numbers, the Strouhal numbers are almost constant over the Reynolds number range. There appears to be two separate curves, the lower one for deep cavities and the

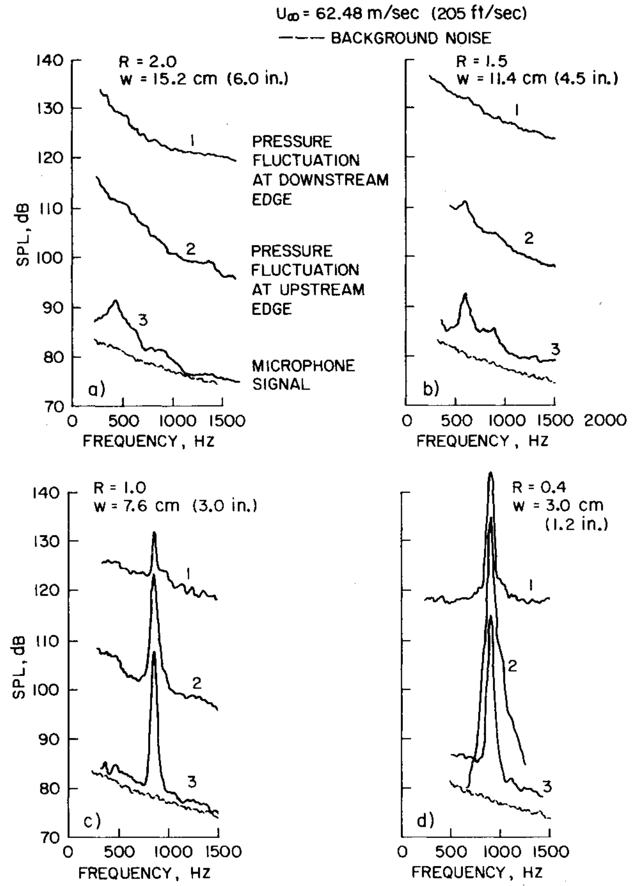


Fig. 7 Frequency spectrum of pressure transducers and a microphone [$\theta = 75°$, $d = 7.6$ cm (3.0 in.)].

higher one for shallow cavities. To aid in the estimation of peak frequencies, we have determined an empirical formula for the Strouhal number S as a function of Reynolds number Re:

$$S = a/Re + b\log Re + c$$

$$a = 0.142 \times 10^5$$

$$b = -0.032$$

$$C = \begin{cases} 0.591 \text{ for deep cavities} \\ 1.171 \text{ for shallow cavities} \end{cases}$$

Drag Coefficient

The cavity drag coefficient Δc_D, defined as the difference of the drag coefficient of the airfoil with and without a cavity, is plotted as a function of freestream Mach number in Fig. 10 and Reynolds number based on cavity width in Fig. 11. Shallow cavities give higher values of Δc_D. Figure 11 shows that there may be a discontinuity in Δc_D around $Re = 2.0 \times 10^6$. This discontinuity appears at the division point between shallow and deep cavities.

Sound Power

At this point, we shall use sound power level to determine which theoretical model is best for predictive purposes. We do this by calculating the sound power for a given R at each velocity, then determine the velocity variation for that R. The directivity pattern of the second pressure level of the dominant frequencies as measured by the microphone array is shown in Fig. 12. From these curves, the acoustic power is obtained by summing the sound pressure levels over all angles, then dividing by the number of points. This is an approximation because the sound pressure levels were measured only between 30° and 150°. Since the sound

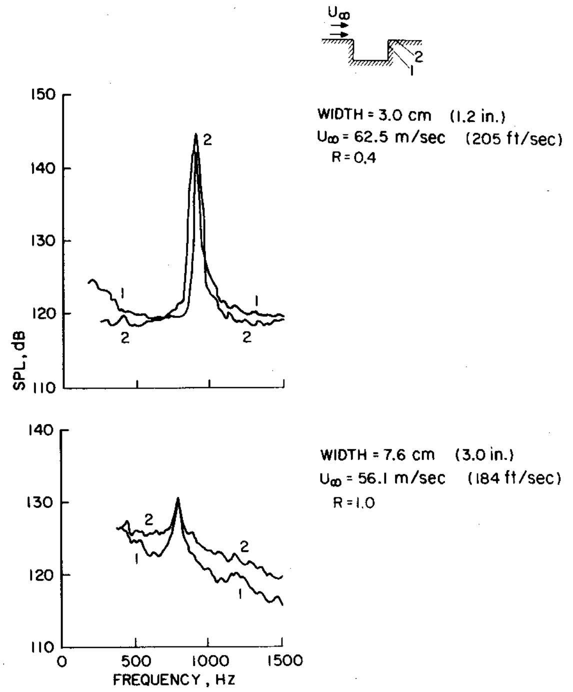


Fig. 8 Frequency spectrum of pressure transducers at the downstream edge [d = 7.6 cm (3.0 in.)].

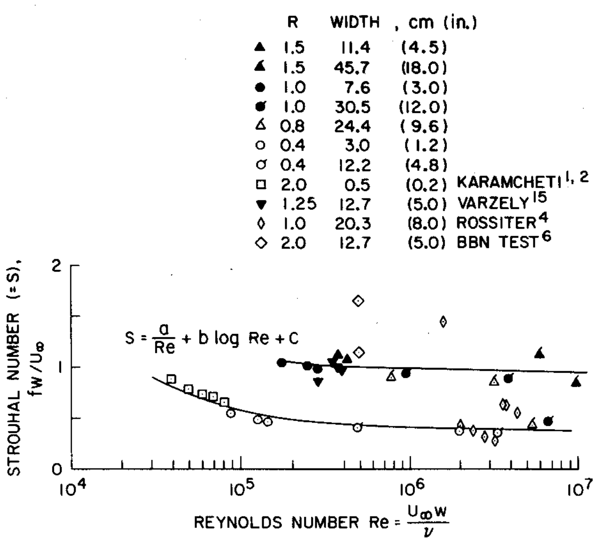


Fig. 9 Strouhal number vs Reynolds number.

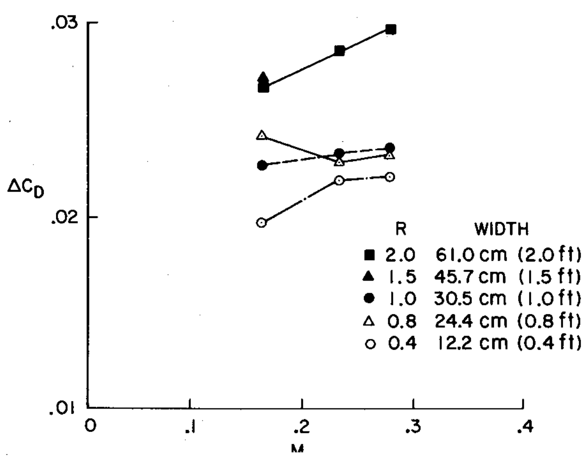


Fig. 10 Drag coefficient vs freestream Mach number.

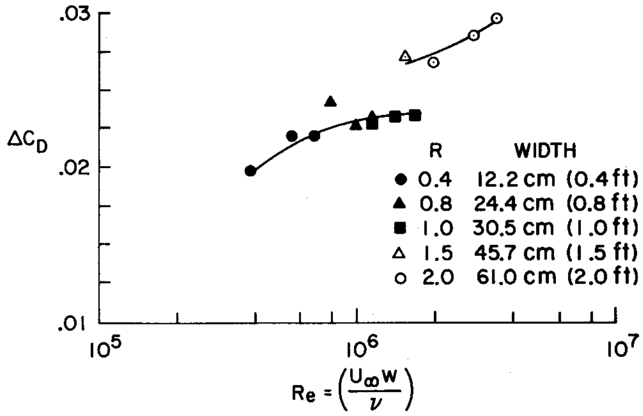


Fig. 11 Drag coefficient vs Reynolds number [d = 30.5 cm (1.0 ft)].

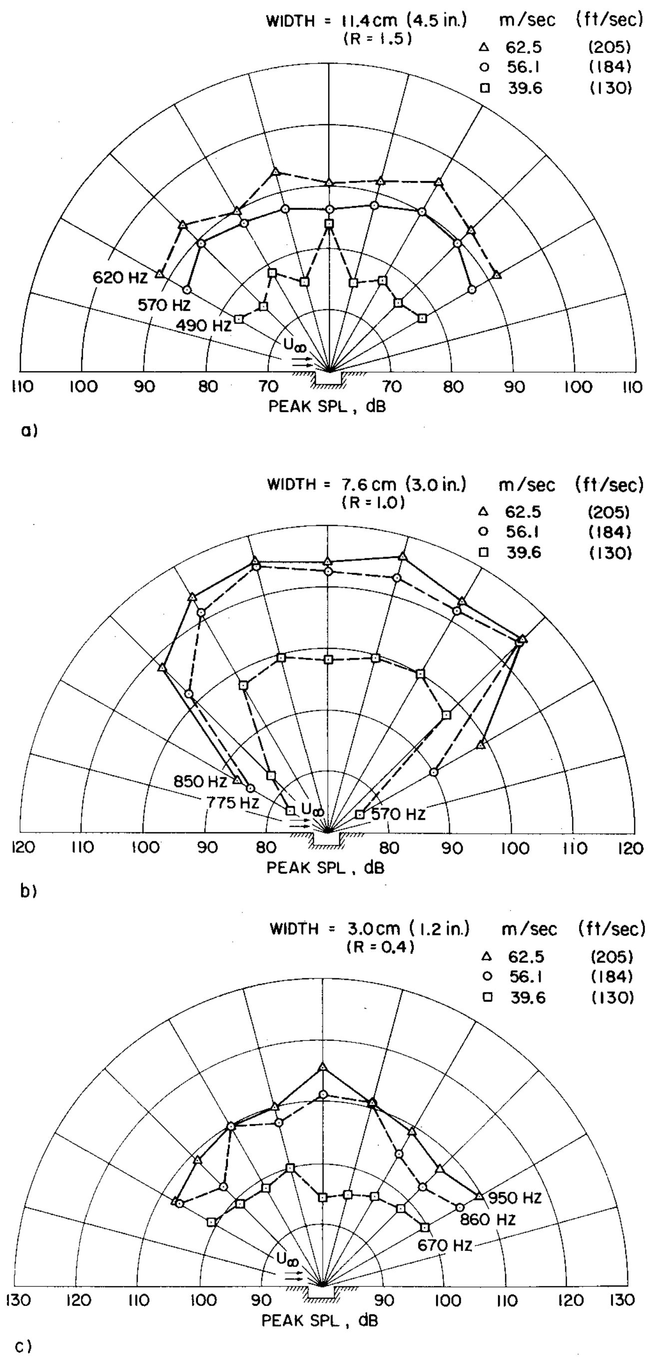


Fig. 12 Directivity pattern of a microphone signal for dominant frequency [d = 7.5 cm (3.0 in.), microphone distance from cavity = 144.8 cm (4 ft 9 in.)].

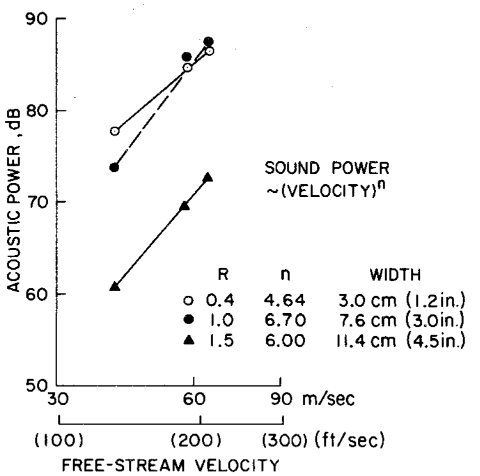


Fig. 13 Acoustic power vs freestream velocity.

pressure level is weighted with $\sin\theta$, the error will be insignificant because $I(\theta)\sin\theta$ would be small for $0° \leq \theta \leq 15°$ or $165° \leq \theta \leq 180°$. These results are shown as a function of the freestream velocity in Fig. 13.

The acoustic power is proportional to the sixth power of the freestream velocity for a shallow cavity. From this observation, the pressure fluctuations on the downstream edge correspond to a dipole type of source located near the downstream edge of the cavity. This dipole model is different from that of a monopole proposed by Bilanin and Covert.[11] But when the upstream edge is much closer to the downstream edge, as in the deep cavity, the upstream edge directly contributes to the far-field noise where sound power is greatly enhanced. In this case, the variation of sound power varies as the 4.7th power of freestream velocity. We can approximate a deep cavity by using a theoretical model of a dipole source located near the downstream edge of the cavity, with the sharp upstream edge of the cavity. With the model of line dipoles with the nearby edge, we were able to calculate a fifth power dependence by using an approach similar to that of point quadrupoles with the nearby edge of a half plane carried out by Ffowcs Williams and Hall[13] and many others.[14]

Concluding Remarks

The measurements of far-field sound pressure level, fluctuating surface pressures, and drag coefficient were presented for large cavities. From an examination of the results, we see that shallow and deep cavities have different types of behavior and will require two different theoretical models. This duality is based on the following experimental evidence:

1) For deep cavities, dominant frequencies exist at both upstream and downstream edges of the cavity, whereas for the shallow cavities there exists a broadband spectrum at the downstream edge.

2) For drag coefficient Δc_D, shallow cavities give higher values than deep cavities. In addition, the drag coefficient appears to have a discontinuity near $Re = 2.0 \times 10^6$. This discontinuity corresponds to the division between shallow and deep cavities.

3) The acoustic power is proportional to the sixth power of the freestream velocity for shallow cavities and is proportional to the 4.7th power for deep cavities.

Based on these observations, two theoretical models can be constructed: 1) for shallow cavities, a dipole located near the downstream edge of the cavity, and 2) for deep cavities, a dipole located near the downstream edge with the superimposed effects of an upstream edge of the cavity.

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