CATEGORY 5: SOUND GENERATION IN VISCOUS PROBLEMS

PROBLEM 2: SOUND GENERATION BY FLOW OVER A CAVITY

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ABSTRACT

The discrete frequency sound produced by the flow of air at low subsonic speeds over a deep cavity was investigated. A long aspect ratio rectangular cavity with a leading edge overhang that cut off ½ of the cavity opening was placed flush with the top surface of a wind tunnel. The approach flow velocity was maintained at 50 m/s for the benchmark problem although results are also presented for other conditions. Boundary layer measurements conducted with a single element hotwire anemometer indicated that the boundary layer thickness just upstream of the cavity was equal to 17 mm. Sound pressure level measurements were made at three locations in the cavity: the center of the leading edge wall, the center of the cavity floor, and the center of the trailing edge wall. Three discrete tones were measured at all three locations with corresponding Strouhal numbers (based on cavity opening length and approach flow velocity) equal to 0.24, 0.26, and 0.41. The amplitudes of each tone were approximately equal at each measurement location in the cavity. Measurements made at other approach flow conditions indicated that the approach flow velocity and the boundary layer thickness affected the frequency characteristics of the discrete tones.

INTRODUCTION

The production of discrete frequency sound by the flow of air over a cavity occurs at low subsonic approach flow speeds for many automotive applications such as those associated with car door gaps and sunroofs, and at high subsonic or supersonic approach flow speeds for many aeronautical applications. The flow is often characterized by complex oscillations of the shear layer, the production of discrete tones as well as broadband noise, and wave motion (longitudinal or transverse) within the cavity. The flow and acoustic phenomena are often broadly categorized by the cavity length (l) to depth (D) ratio, with values of l/D below one indicating deep cavities and values of l/D greater than one indicating shallow cavities (refs. 1 and 2). Experiments have shown (ref. 3) that the shear layer oscillations associated with shallow and deep cavities are fundamentally different. The cavity wave motion may also be significantly different for these two cases with longitudinal waves occurring for deep cavities and transverse waves occurring for shallow cavities. While the resulting discrete frequencies produced by shallow cavities are often well described by Rossiter's equation (ref. 4), the frequencies produced by deep cavities may significantly deviate from the values predicted by this early model. Helmholtz type resonances have also been observed for some cavity geometries.

The broad range of flow and geometric parameters affecting the production of cavity tones makes the development of general flow and sound production models somewhat difficult. Experimental investigations have shown (ref. 5) that the amplitude and frequency of discrete tones are affected by the type of boundary layer (laminar or turbulent) and the boundary layer thickness. The type of boundary layer also affects the appropriate scaling parameters relating the boundary layer thickness and the Strouhal number of the discrete tones. The many parameters governing the cavity mouth geometry can also have a significant impact on the resulting acoustic production and flow field characteristics (refs. 6 and 7).

The cavity problem chosen for the 4th Computational Aeroacoustics Workshop on Benchmark Problems is one somewhat resembling the door gap of an automobile although slightly larger dimensions have been used for experimental purposes. The approach flow is at low subsonic speeds but well above that associated with an automobile. The purpose of the higher velocity is to ensure that a strong acoustic resonance is produced by the numerical models and in the experiments. The geometry of the cavity mouth is similar to that of the door gap and also introduces additional complication to the problem that may result in multiple types of flow resonances.

BENCHMARK PROBLEM STATEMENT

Air flows over the cavity shown below with a mean approach flow velocity of 50 m/s. The boundary layer that develops over the flat plate is turbulent with a thickness of 14 mm at the entrance to the cavity. Calculate the power spectra at the center of each cavity wall and the center of the cavity floor.

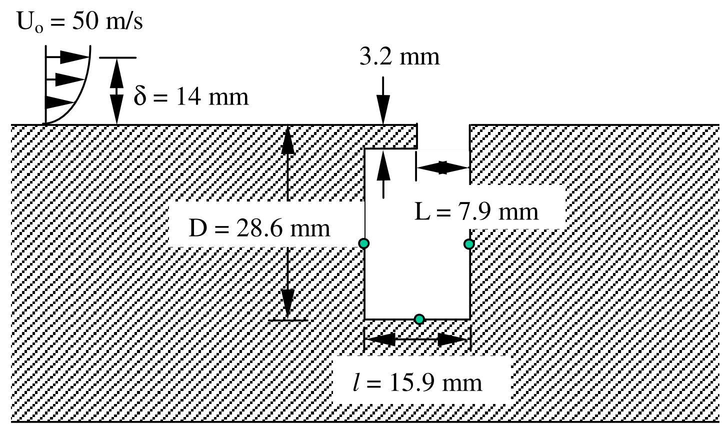


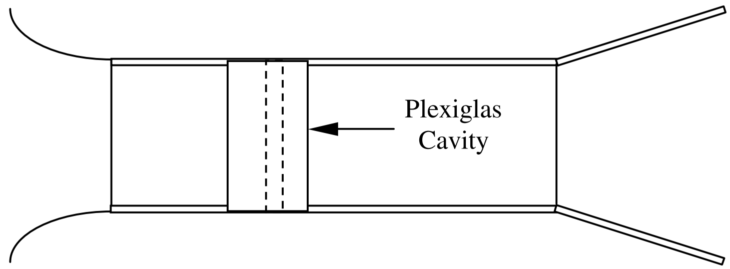
Figure 1. The cavity geometry used for the benchmark problem. The microphone measurement locations are indicated by a● .

EXPERIMENTS

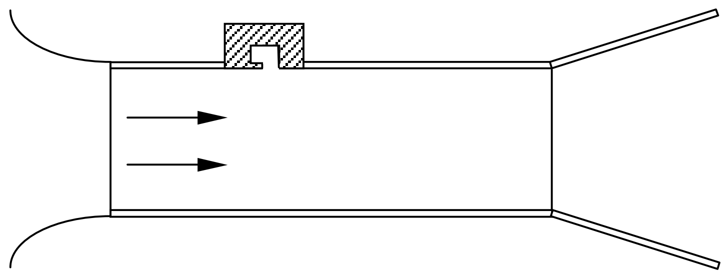
The experiments were conducted in the 0.46 m x 0. 46 m test section of the recirculating wind tunnel at Kettering University. The tunnel was equipped with silencers before and after the fan.

The Plexiglas cavity shown in Fig. 2 was placed along the upper surface of the wind tunnel and spanned the entire tunnel cross section. End caps were placed at the outer edges of the cavity so that only the cavity mouth remained open to the flow. Condenser microphones, 6.35 mm in diameter, were mounted in the center of the cavity leading edge wall, the center of the cavity trailing edge wall, and the center of the cavity floor at a single cavity cross-section. The resulting power spectra were obtained with an 8 Hz bandwidth FFT.

Boundary layer measurements were made with a single element hot wire anemometer traversed vertically near the wind tunnel top surface at different axial locations in the test section. A continuous test section surface (no cavity present) was used during the boundary layer studies. Although the benchmark problem statement called for a boundary layer thickness of 14 mm, the boundary layer studies indicated that the thickness of the boundary layer at a location corresponding to the cavity entrance was 17 mm when the approach flow velocity was 50 m/s. Additional acoustic measurements were made for a second axial position in the test section 65 cm upstream of the original cavity location. The boundary layer was thinner in this region of the test section. Measurements made at the second location served to determine the sensitivity of the acoustic radiation to changes in the boundary layer thickness.



(a)



(b)

Figure 2. Schematics of the wind tunnel test section with the cavity showing (a) the top view and (b) the side view.

RESULTS

The results for the benchmark problem as well as results for the same cavity with different approach flow conditions will be presented in the following two sections. The additional results are intended to further clarify the sensitivity of the resulting acoustic radiation to changes in the approach flow.

Benchmark problem

The power spectra obtained from the cavity measurements are shown in Fig. 3. The corresponding locations of the microphones are also indicated on the plot. Three discrete peaks with frequencies equal to 1504 Hz, 1624 Hz, and 2616 Hz are observed in the spectra. The corresponding Strouhal numbers are 0.24, 0.26, and 0.41, respectively, where the Strouhal number is given by $\frac{fL}{U_o}$. The sound pressure levels of the discrete peaks are approximately equal at each location in the cavity cross-section.

It is not possible to determine the nature of the flow resonance associated with each discrete tone in Fig. 3 from the spectral data. However, it is possible to perform some rough calculations and compare with other published data to determine the likely type of resonance associated with the three peaks. If a cavity mode (longitudinal) coupled with the shear layer oscillations in the cavity mouth, the first cavity mode would result in a resonant wavelength equal to four times the cavity dimension, D, or a resonance frequency of 3016 Hz. The second mode would result in a resonance frequency of 1508 Hz, a value remarkably close to that of the lowest discrete frequency in Fig. 3. The second peak in the spectrum, 1624 Hz, produces a Strouhal number consistent with that measured by De Metz and Farabee (ref. 5) for cylindrical deep cavities with approach flow velocities similar to those used in the present investigation. In the experiments of De Metz and Farabee, the tone was attributed to the second cavity resonance mode although phase measurements within the cavity were not made in the experiments. It is possible that the tone at 1624 Hz is associated with a longitudinal cavity resonance for an effective depth less than 28.6 mm. The reduction in effective cavity depth could be due to the complicated cavity mouth geometry and the complicated shear layer oscillations in this region of the flow.

The tone at 2616 Hz is most likely associated with an edgetone type resonance. The feedback criterion applied to the cavity (refs. 8 and 9) is given by

$$\frac{N+p}{f} = \int \frac{dL}{u_{con}} + \frac{L}{c},$$

where N is an integer, p is a fraction accounting for the delay between a particular phase of the flow disturbance and the resulting acoustic wave (equal to ¼ for the edgetone), u_{con} is the convection velocity of the shear layer disturbances, and c is the speed of sound. The above equation assumes that the sound is produced at the trailing edge of the cavity. The first term on the right hand side of the equation accounts for the travel time of the shear layer disturbances while the second term accounts for the propagation time of the acoustic wave from the sound source to the leading edge of the cavity. Since the acoustic wavelengths are large compared to L, the second term may be neglected. Assuming that N is equal to one and a value of ¼ is used for p, the resulting calculated acoustic frequency is equal to 2610 Hz when a convection velocity of $0.33U_o$ is used for the shear layer disturbances. The value for the convection velocity was obtained from the measurements of De Metz and Farabee. The calculated value is quite close to the measured frequency of the third discrete peak in the spectra of Fig. 3.

Although Helmholtz type resonance has been observed in many cavity flows, calculations for the cavity geometry used in the benchmark problem indicate that frequencies close to 1000 Hz would be observed in the spectrum for this type of resonance. All of the measured discrete frequencies are all well above this value. Additionally, if the cavity displayed three-dimensional affects, it would be possible to obtain wavelengths on the order of the width of the wind tunnel test section (0.46 m). All of the measured discrete frequencies in the spectra correspond to wavelengths much shorter than this dimension. It is, therefore, unlikely that either of these types of resonances were present in the flow. However, additional measurements are necessary to determine the exact origin of each tone in the spectra.

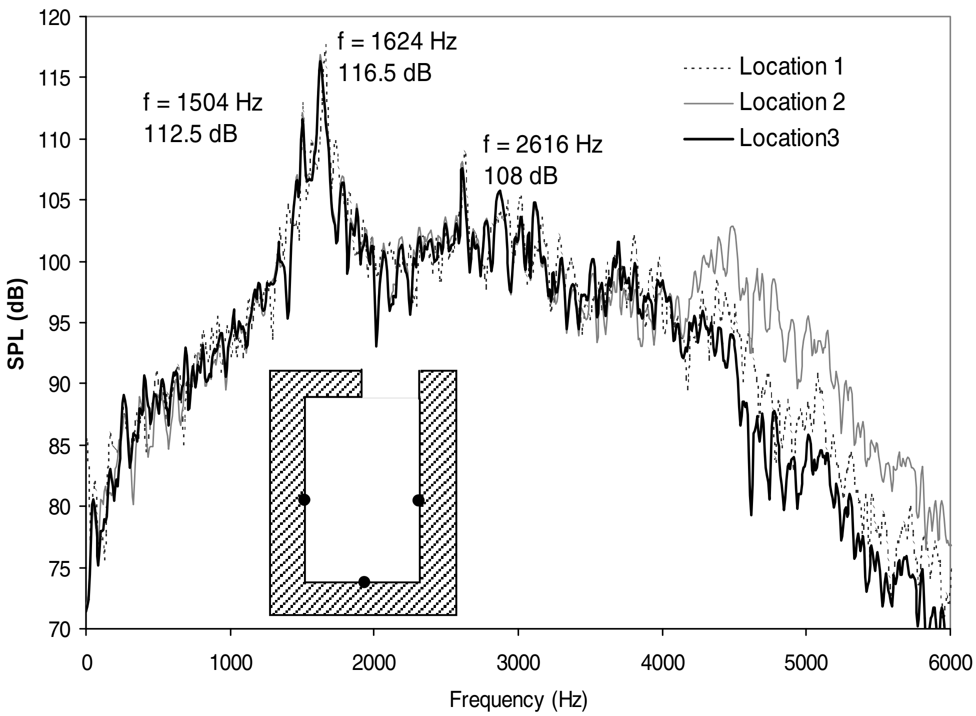
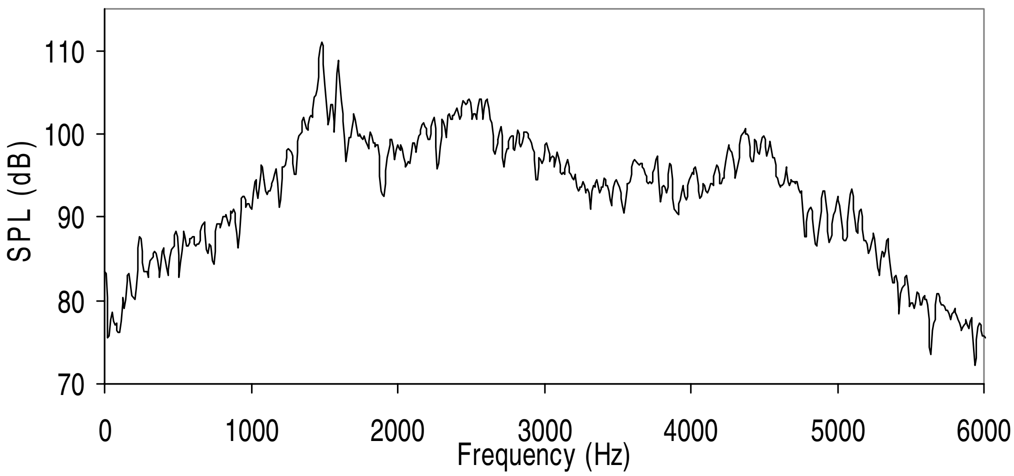


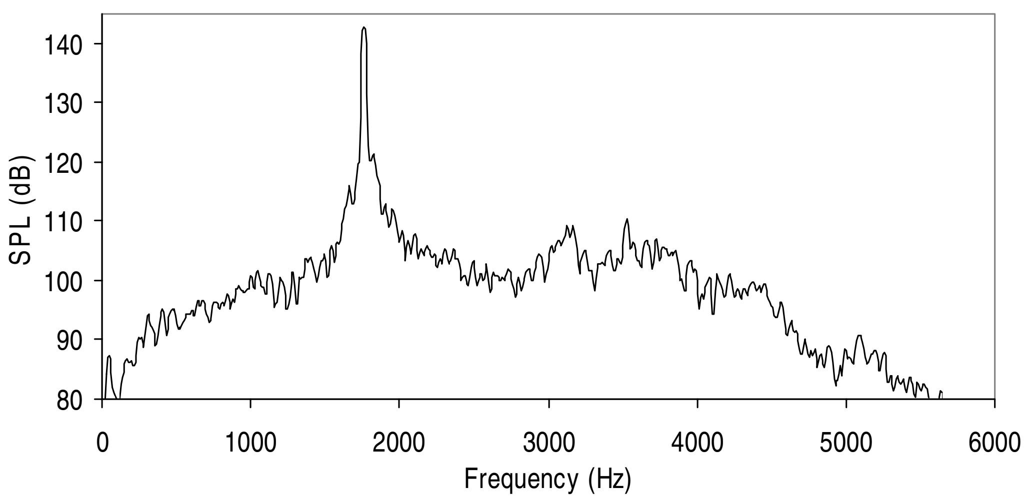
Figure 3. The power spectra obtained at the three microphone locations indicated in the figure.

Results at other approach conditions

Cavity sound pressure level measurements were made for other approach flow velocities with the cavity located at the same axial location in the test section as that used in the benchmark problem. Although sound pressure level measurements were made at the three microphone locations indicated in Fig. 1, results will only be presented for one microphone location since similar spectra were obtained at all three locations. The power spectra shown in Figs. 4 (a) and (b) were obtained for approach flow velocities equal to 45 m/s and 60 m/s, respectively. By comparing Figs. 3, 4 (a), and 4 (b), it can be seen that multiple discrete peaks are observed in the spectra obtained with approach flow velocities between 45 and 50 m/s, while and a single dominant peak is present in the spectrum obtained at an approach flow velocity of 60 m/s. When a single discrete peak is present, the sound pressure level of the tone is much higher than that associated with the dominant peak of the spectra when multiple tones occur. This result would indicate that the energy is divided among the resonant modes when multiple tones are produced. This could have implications for computational results that do not properly reproduce all of the resonance modes observed in the experiments.



(a)



(b)

Figure 4. The power spectrum obtained in the cavity for approach flow velocities equal to (a) 45 m/s and (b) 60 m/s.

The power spectrum in Fig. 5 was obtained when the cavity was moved 65 cm upstream in the test section from the location used in the benchmark problem. At this location in the tunnel, the boundary layer was thinner than 17 mm. The multiple peaks in the spectra of Fig. 3 are no longer present for the thinner boundary layer although the approach velocity is equal to 50 m/s for both cases. Additionally, the peak sound pressure level in Fig. 5 is greater than the peak sound pressure level in Fig. 3 indicating that boundary layer thickness affects both the frequency characteristics and the amplitude of the dominant peak in the spectrum. De Metz and Farabee (ref. 5) found that the Strouhal number for the dominant tone was affected by the normalized boundary layer thickness where the length of the cavity mouth was used for the normalization. The results are consistent with the present experiments which indicate that the Strouhal number increases with decreasing boundary layer thickness. The sensitivity of cavity tones to boundary layer changes could have a significant impact on numerical models used to represent this type of flow.

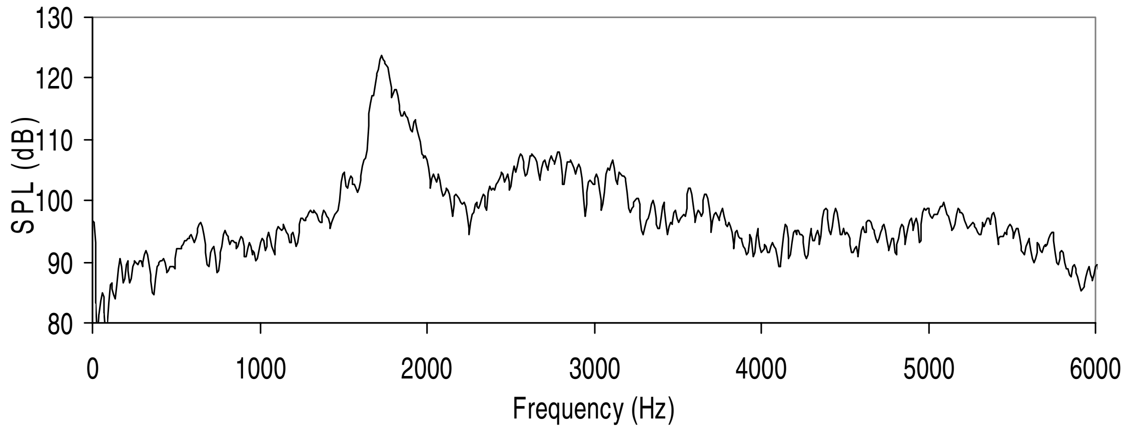


Figure 5. The power spectrum obtained in the cavity for an approach flow with a thin boundary layer and a velocity equal 50 m/s.

DISCUSSION AND RELEVANT CONSIDERATIONS FOR COMPUTATIONAL COMPARISONS

The intent of benchmark problems is to provide a means to test the ability of numerical schemes to properly predict flow fields and acoustic radiation. As the flow fields become more complicated, experimental data may be the only results available for comparison. However, it is important to understand the experiments and the sensitivity of the flow field to changes that may occur during the experiment investigation. In many cases, the numerical problem may be far more “perfect” than the real world experiment. In other cases, the models used in the numerical schemes may lead to significant numerical errors that cause the results to deviate significantly from that observed in experiments. Emphasis should be placed on the ability of the numerical scheme to predict trends observed in experiments.

The ability to properly represent the boundary layer in the experiments and the numerical models was perhaps the most difficult problem faced in this benchmark problem. Any small experimental error in the boundary layer thickness measurement could easily be on the order of a significant fraction of the cavity mouth dimension due to the small value of L. Additionally, the introduction of the cavity to the test cell could result in small imperfections that lead to a thicker boundary layer than that measured for the test section without the cavity. The ability to properly represent the boundary layer in a numerical scheme also presents a problem for this type of flow. Experiments have shown that the tonal characteristics associated with cavities introduced in flows with laminar boundary layers are significantly different from those associated with cavities introduced in flows with turbulent boundary layers. It is only reasonable to expect that calculated frequency characteristics will also be affect by numerical turbulence and boundary layer models.

For this type of flow, it may be sufficient to have a numerical scheme that predicts trends observed in the experimental data. Since it is often difficult to obtain exact experimental values across facilities, it may be unrealistic to expect an exact comparison between experimental data and numerical results. In the present experiments, the peak sound pressure levels were quite similar at all three locations in the cavity for a given approach flow condition. As the approach flow velocity increased, multiple tones disappeared and a single discrete peak was present in the acoustic data. If multiple tones were present in the spectra associated with a thick boundary layer, thinning the boundary layer tended to lead to a single discrete peak. The Strouhal numbers for the dominant peak were between 0.26 and 0.27 for all flow conditions investigated. When the approach flow velocity was equal to 50 m/s, the measured peak sound pressure level was between 116 dB and 123 dB. Perhaps a successful numerical scheme is one that that successfully predicts the data trends noted above. A final test of the scheme should involve comparing the computed flow field data to that measured by techniques such as particle image velocimetry.

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