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Rectangular and Modified Two-Dimensional Cavities in an Open-Jet Anechoic Wind Tunnel at Low Mach number

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Abstract

Experimental investigations are presented of noise from flow over unmodified and modified two-dimensional cavities at low Mach number, using an open-jet anechoic wind tunnel facility. The Reynolds numbers based on cavity depth were Re_D=4100-16500. Four cavity lengths were tested, which gave length-to-depth (*L/D*) ratios of 1.17, 2.33, 3.5 and 4.67. There was a thin laminar boundary layer upstream of the cavity. The cavity was modified using sloped walls, a passive control technique for cavity flow noise. Such modifications were found to, typically, reduce overall sound pressure levels and to reduce the number or intensity of acoustic tones.

Introduction

Cavity flow noise can serve as a source of annoyance in an automotive context [7] where cavities can be found around side mirrors and roof racks. There can also be dangerous structural implications in high-speed aerospace applications [1], where cavities can be formed by aircraft weapons bays and wheel wells and can contribute to structural fatigue or malfunction of equipment [5]. The high noise levels produced by certain cavities can be attributed to broadband noise mechanisms as well as feedback-driven oscillations of the unstable shear layer that forms over a cavity [7].

Rossiter [9] and Sarohia [10] developed key equations for estimating the frequencies and occurrence of cavity oscillations respectively. Equation 1 is Rossiter's [9] equation which predicts possible oscillation frequencies, where α is the phase delay as a fraction of a wavelength and $\kappa=U_c/U$ is the mean convection velocity ratio of disturbances along the cavity. Sarohia's [10] criterion (equation 2) describes the minimum non-dimensional cavity length for oscillations to occur, based on the upstream boundary layer thickness.

$$St = \frac{fL}{U} = \frac{n-\alpha}{M + 1/\kappa} \qquad n = 1, 2, 3... \tag{1}$$

$$\frac{L}{\delta_0}\sqrt{\mathrm{Re}_{\delta_0}} > 290 \qquad \text{(for oscillations)} \tag{2}$$

Geometric modifications to the cavity walls are well established as a simple and effective method of reducing cavity noise [2, 3]. Such modifications can include sloped front or rear walls. The modifications typically afford passive control that reduces shear layer instabilities. Modifications have been observed to stabilise the shear layer by thickening it [3]. Modifications can change the flow near the points of separation at the front of the cavity and reattachment (or impingement) at the rear of the cavity. One modification has been observed to deflect the shear layer and reduce impingement on the rear wall [2].

Although studies have been carried out in industry [7] and consulting to alleviate oscillatory cavity noise from small low-speed 2D cavities using geometric modifications of some sort (for example, in an automotive context), there are few regarding bulk-style geometric modifications on 2D low-speed cavities at very low Mach number in the literature. Milbank [7] investigated 2D cavities with a laminar boundary layer in an open-jet semi-anechoic wind tunnel, however mainly rectangular cavities (including the effect of yaw) were considered. Harper [4] considered the far-field noise levels and flow around modified 2D cavities at low speeds with a turbulent boundary layer, however the cavity shape was based on a car roof rack extrusion and quite different to a standard rectangular cavity. Ozalp *et al.* [8] investigated rectangular, triangular and semi-circular cavities with a turbulent boundary layer using Particle Image Velocimetry (PIV) in a water tunnel. Although the cavities were non-oscillatory, lower levels of "noise" were found in the velocity spectra of the modified cavities. To extend these studies, experimental investigations of noise from flow over unmodified and modified two-dimensional cavities at low Mach number are presented.

Method

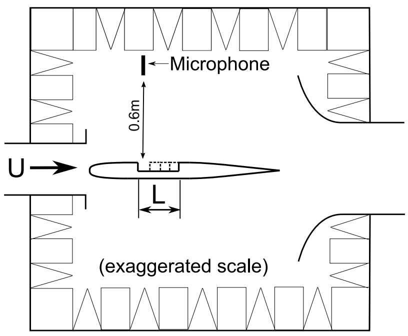

Figure 1: Sketch of flat-plate/airfoil with cavity in anechoic wind tunnel chamber. Cavity can be varied to give 4 different lengths.

Two-dimensional oscillatory cavities were formed by a slot in a flat-plate/airfoil (figure 1). They were investigated using the University of Adelaide open-jet anechoic wind tunnel (AWT) facility (described in [6]). The AWT consists of a 2 × 2 × 2 m^3 anechoic chamber into which a jet of 275 mm × 75 mm discharges. The flat-plate/airfoil had a super-elliptic leading edge and a tapered trailing edge, and was placed in the jet outlet. For a fixed depth of *D*=6mm, four cavity lengths were tested giving length to depth (*L/D*) ratios of 1.17, 2.33, 3.5 and 4.67. The free-stream velocity range was *U*=10-40 m/s (*M*=0.03-0.12) giving a Reynolds number based on cavity depth of Re_D=4100-16500. Selected cavities were modified using front and/or rear walls sloped at 45°, with the cavity volume being maintained constant. Far-field noise measurements were taken using a microphone at 0.6m from the flat plate. Velocity measurements were taken with single-wire hot wire probes using a TSI IFA300 hot wire anemometer.

Boundary Layer Profile

The cavity was found to have a thin laminar upstream boundary layer (δ<1mm). A single-wire hot wire probe was positioned as close as practical to the leading edge of the cavity and traversed vertically to produce the plot in figure 2. Although the plate was mounted at a 1° nose-down angle, the similarity to the Blasius boundary layer profile for flow on a flat plate at zero angle of attack shows that a laminar boundary layer is present ahead of the cavity.

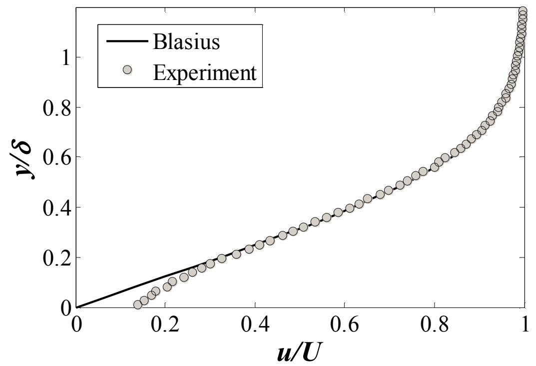

Figure 2: Shear layer profile close to the leading edge of the cavity at nominal jet velocity of 30 m/s.

Rectangular Cavities

Comparisons of far-field noise spectra and velocity spectra taken in the cavity shear layer showed strong coherence, suggesting that the audible oscillatory noise from the model did indeed originate in the cavity shear layer. The strength of the far-field noise radiated can give a good indication of the strength of oscillations in a cavity [7]. The spectrograms of far-field sound pressure level shown in figure 3 reasonably clearly illustrate the development of the cavity tones with velocity and increasing cavity length. At *L*/*D*=1.17 cavity oscillations began from upwards of approximately *U*=23 m/s, similar to the prediction from Sarohia's [10] criterion (equation 2). There is a dominant cavity tone and several other distinct prominent cavity tones. At *L*/*D*=2.33 a stage jump is evident at a nominal velocity of approximately 17 m/s, with the new modes appearing before the previous modes cease. Again the tones are quite distinct from the background levels and there is a dominant tone. The tones progressively drop in frequency for *L*/*D*=3.5 and *L*/*D*=4.67, and there are more modes present – up to four to five modes each having relatively similar amplitude, unlike the dominant modes found in the shorter cavities.

For *L*/*D*=1.17, the light coloured area at approximately *f*=500-1000 Hz, below *U*=23 m/s, corresponds to a possible airfoil self-noise mechanism of the overall airfoil. Regardless of velocity, this broad tone ceased once cavity oscillations began to occur (therefore not interfering with cavity noise measurements).

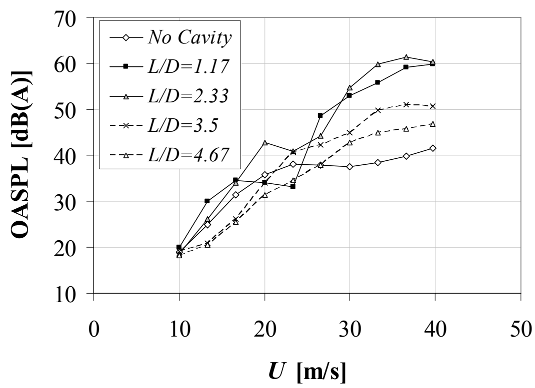

Figure 4: Overall sound pressure levels for the rectangular cavities

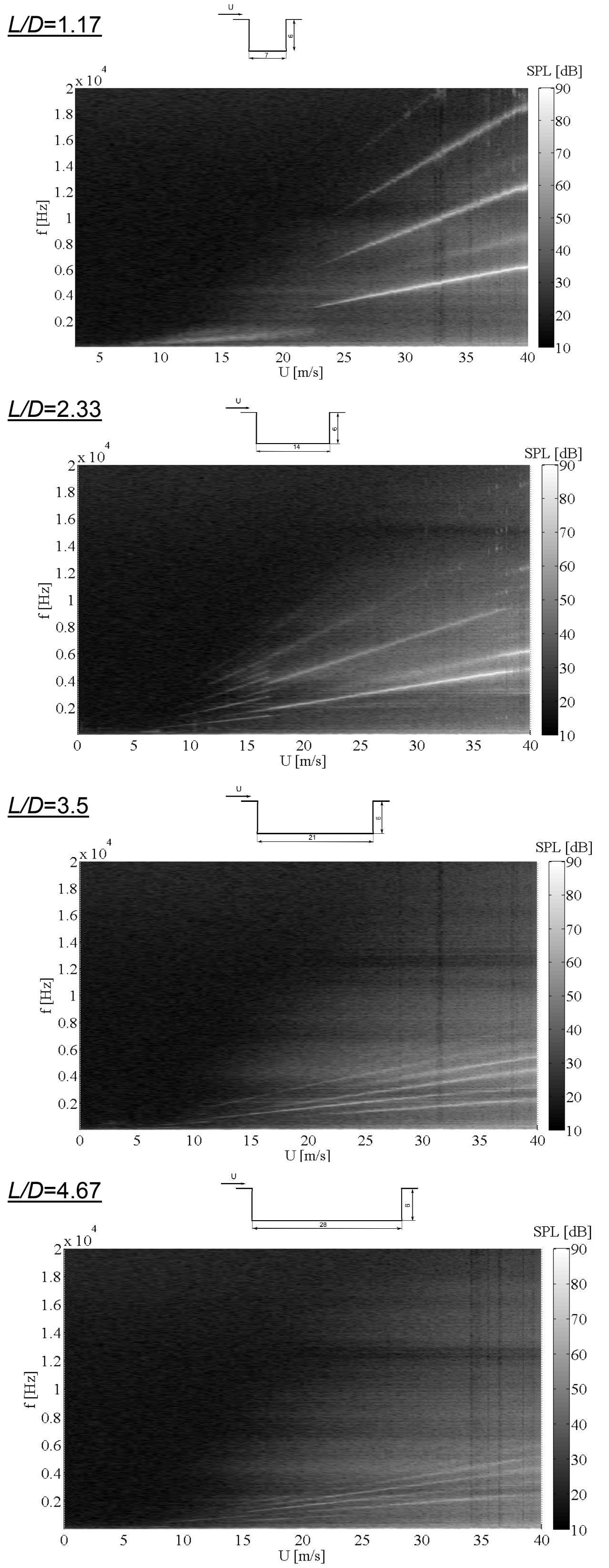

Figure 3: Spectrograms for the four cavity lengths, showing far-field sound pressure level against frequency and nominal velocity.

Figure 4 shows the overall sound pressure level (OASPL) for the rectangular cavities plotted against the nominal free-stream velocity. The shorter cavities (*L*/*D*=1.17 and *L*/*D*=2.33) are the loudest. Interestingly the case without the cavity is louder at lower velocities than the longer two cavities, due to the airfoil self-noise mechanism.

Modified Rear Walls at *L/D*=1.17 and *L/D*=3.5

L/D=1.17

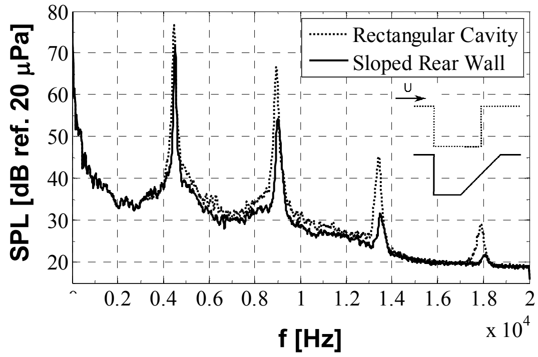

Figure 5: Comparison of far-field sound spectra for rectangular and sloped rear wall cavity at *L/D*=1.17 for nominal *U*=30 m/s.

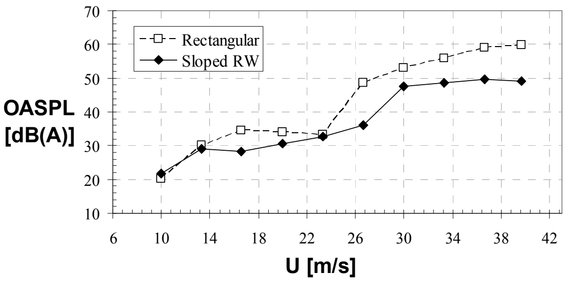

Figure 6: Overall sound pressure level versus velocity for *L/D*=1.17.

For *L/D*=1.17, the use of a sloped rear wall produced a reduction in the intensity of tones at 30 m/s, with a small reduction of the main tone at 4.5 kHz and larger reductions in the other tones (figure 5). Figure 6 shows that there was typically a reduction in overall sound pressure level (OASPL) after the onset of cavity oscillations at *U*~23 m/s.

L/D=3.5

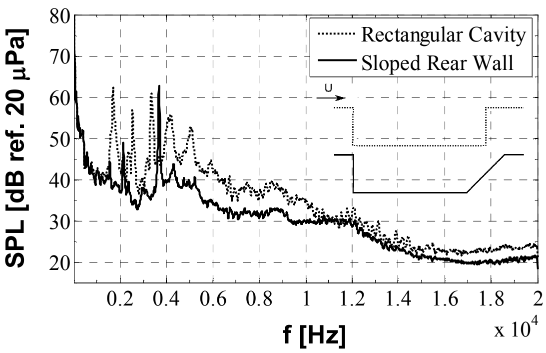

Figure 7: Comparison of far-field sound spectra for rectangular and sloped rear wall cavity at *L/D*=3.5 for nominal *U*=30 m/s.

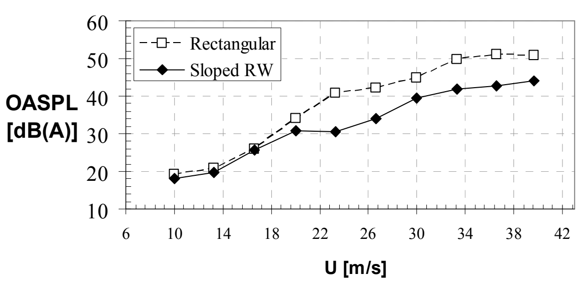

Figure 8: Overall sound pressure level versus velocity for *L/D*=3.5.

For *L/D*=3.5, the use of a sloped rear wall produced a reduction in the number, but not intensity, of tones at 30 m/s as well as a reduction in broadband noise levels (figure 7). There was a reduction in OASPL across the range of velocities above *U*=16 m/s (figure 8).

Modified Cavities at *L/D*=2.33

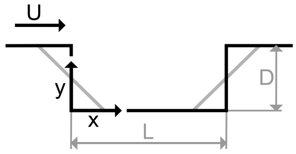

Figure 9: Co-ordinate system for compared cavities at *L/D*=2.33, showing sloped walls.

The modified and rectangular cavities compared at *L/D*=2.33 were formed slightly further downstream than the other tested cavities, to allow for rectangular or sloped inserts to be placed at both the front and rear walls. Figure 9 shows the co-ordinate system for these cavities.

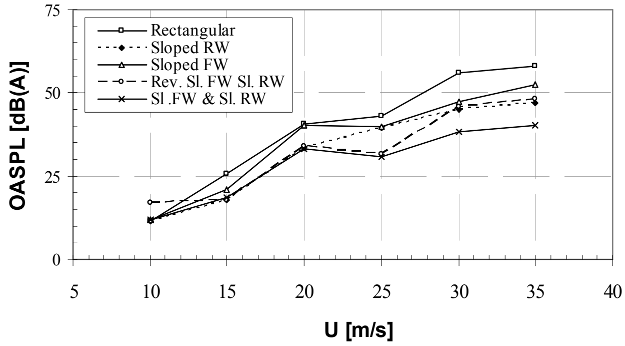

Figure 10: Overall sound pressure level against velocity for *L/D*=2.33.

U (m/s)	Attenuation (dB)			
10	0	-0.5	-5.7	-0.3
15	7.9	4.8	7.9	7.0
20	7.3	0.4	6.7	7.6
25	3.4	3.0	11.5	12.1
30	10.8	8.7	10.1	17.5
35	11.1	5.5	10.1	18.0

Table 1: Attenuation of OASPL (compared to rectangular cavity) given by the various modified cavities at *L/D*=2.33.

The modified cavities tested at *L/D*=2.33 are shown in the column headings of table 1. They included a sloped front wall and a "reverse" sloped front wall combined with a sloped rear wall. Figure 10 shows the OASPL produced by these cavities in dB(A). All of the modifications produced some attenuation of OASPL across most of the velocity range (table 1). Sloped front *and* rear walls were found to produce the largest attenuation.

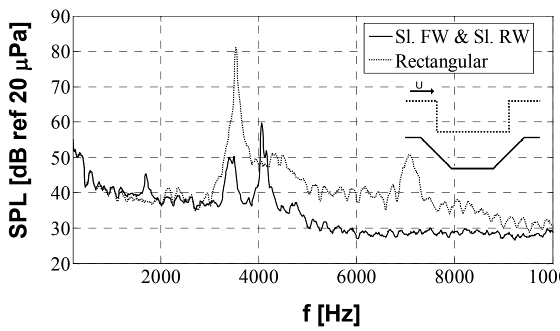

Figure 11: Comparison of far-field sound spectra for Rectangular and Sloped FW & Sloped RW cavity at nominal *U*=30m/s.

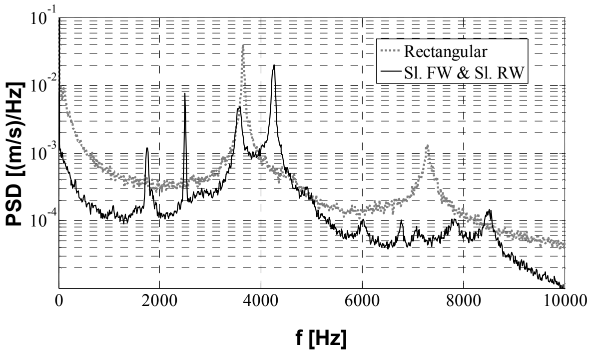

Figure 12: Comparison of velocity spectra at x/L=0.79 and y/D=1.16, for nominal U=30 m/s.

Figures 11 and 12 show a comparison of the acoustic and velocity spectra respectively for the rectangular cavity and cavity with sloped front and rear walls at 30 m/s, taken at a position just above the cavity and towards the rear. Figure 11 shows that the SPL of the main tone is reduced by around 20 dB for the modified cavity. Interestingly, the velocity spectrum shows a switch from two distinct peaks of cavity oscillation in the rectangular cavity, to multiple peaks in the modified cavity.

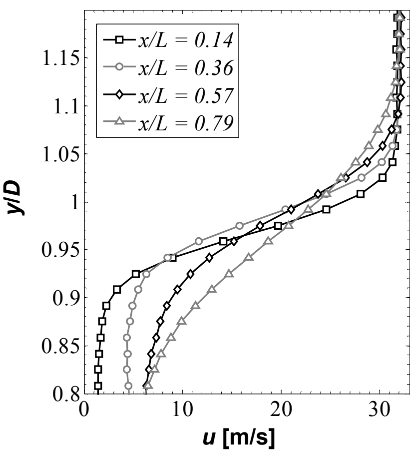

Figure 13: Velocity profiles in cavity with sloped front and rear walls for L/D=2.33 at nominal U=30 m/s.

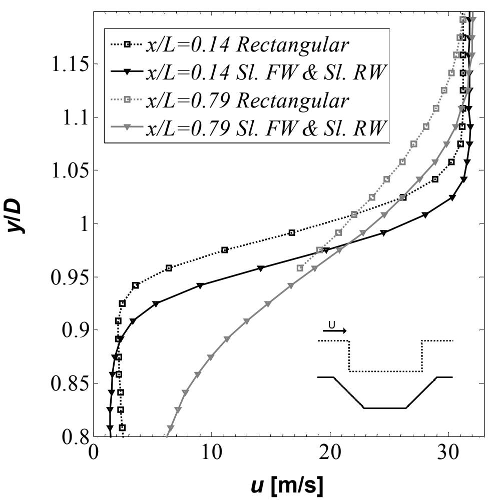

Figure 14: Velocity profile comparison between rectangular and sloped front and rear wall cavity at nominal U=30 m/s.

Velocity profiles in the modified cavity and a comparison to the rectangular cavity, are shown in figures 13 and 14 respectively. As would be expected, the velocity profiles are "fuller" for the cavity with sloped front and rear walls, as the leading edge of the cavity may have effectively been moved further upstream.

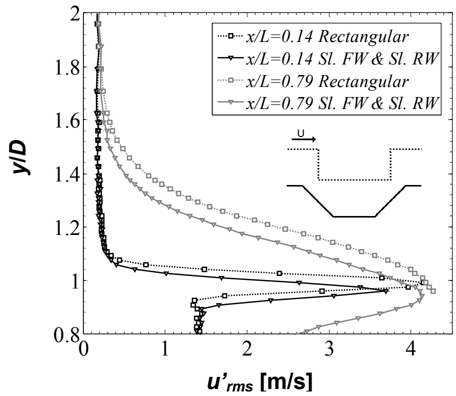

Figure 15: Comparison of u'_{RMS} between the rectangular cavity and the cavity with sloped front and rear walls at nominal U=30 m/s.

Comparing the root-mean-square of fluctuation velocity between the rectangular cavity and cavity with sloped front and rear walls, the levels were found to be slightly lower in the modified cavity at nominal 30 m/s (figure 15).

Conclusions

Sloped walls have been trialled as a passive control measure on 2D cavities with a laminar upstream boundary layer at low Mach number. It was found that modified cavities usually produced a reduction in the intensity or number of tones. There was also typically a reduction in far-field OASPL.

Acknowledgments

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