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An Instance of Cavity Resonance Interaction with an Open-Jet Tunnel Free Shear Layer

J. Milbank[1], S. Watkins[1] and R. Kelso[2]

[1]Department of Mechanical & Manufacturing Engineering
RMIT University, Melbourne, Victoria, 3083 AUSTRALIA

[2]Department of Mechanical Engineering
University of Adelaide, Adelaide, South Australia, 5005 AUSTRALIA

Abstract

Using an aeroacoustic open-jet open-circuit tunnel a study into feedback resonance at small cavity scale and low subsonic flow speeds was undertaken. During the preliminary tests the cavity resonance appeared to be affected by another mechanism, and was not a pure feedback resonance. The resonance peaks were broad, frequency shifted, with many secondary peaks existing on the main peak. An investigation was performed to determine whether the alignment of the model containing the cavity, or its proximity to the test facility free shear layer, were the cause of the unusual resonance characteristics. The results seem to show that the model alignment makes the resonance more or less susceptible to interaction with other mechanisms, but proximity to the test facility free shear layer is, in this case, the cause of the observed characteristics.

Introduction & Objective

The phenomenon of feedback resonance caused by a fluid flowing over a cavity or gap in a surface has been studied in detail for over four decades. Although there is ample material on feedback resonance (sometimes called shear layer tones) in the established literature, there are limited studies involving low subsonic Mach numbers and small cavity scales applicable to automotive applications. On external automotive features such as rear view mirrors, cavities are typically of the order of millimetres in length, with length to depth ratios between 0.1 and 5 but centred around 1, and usually large span-to-length ratios of at least 10. The typical flow speeds in automotive studies range between 17 m/s (60 km/h) and 44 m/s (160 km/h). Sarohia [6] is one of the few researchers that has published experimental results in this range, while others, such as Mendoza & Ahuja [1] and Neary & Stephanoff [4] have tested with cavity scales that are significantly larger than that discussed above. The research into feedback resonance has typically focused on cavity scales and flow speeds that are appropriate for aerospace applications, with other applications seldom considered.

An aeroacoustic open-jet wind tunnel was developed to facilitate the testing of cavities at low subsonic Mach number and small geometrical scale [2]. Recently, a semi-anechoic chamber at the jet exit was added to provide a better test environment for the measurement of cavity noise. Preliminary testing of a comparatively large cavity in this facility (see Figure 1) showed the character of the cavity noise spectrum to be unlike that typically shown in the literature for feedback resonance, [2, 3 & 5]. It was suspected that the close proximity of the test facility jet shear layers to the cavity shear layer might be influencing the resonance, with some interaction occurring between the resonance and jet shear layers. This paper details the steps taken to determine the cause of the unusual resonance quality, and ultimately provide a test environment that produces uncontaminated feedback resonance for the subsequent research program.

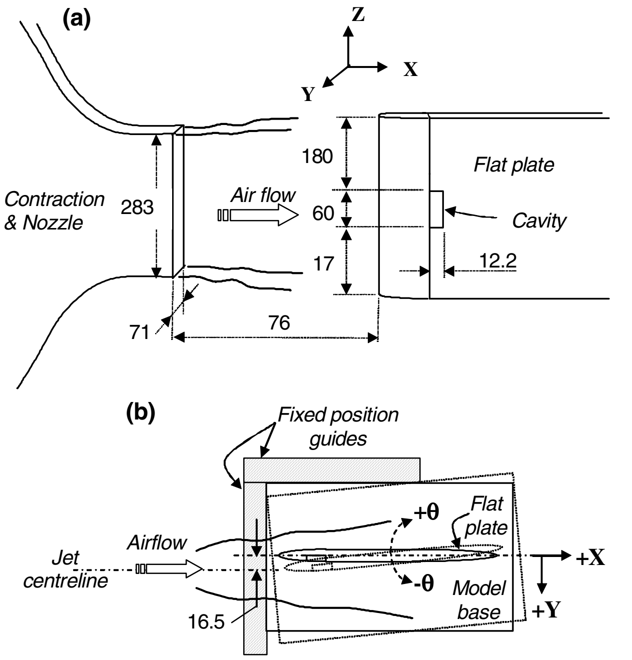

Figure 1. Schematic diagram of cavity model test set-up in the small aeroacoustic open-jet wind tunnel. (a) Side view, (b) Plan view. All dimensions in millimetres.

Background & Experiments

During initial sound measurements with the cavity in the flat plate model, it was observed that small differences in alignment of the cavity model relative to the flow direction resulted in significant differences in the sound spectra as shown in Figure 2. The resonance peaks were broad with many secondary peaks on them, with an increase in the number of secondary peaks with the slight change in model alignment. The test set-up used is shown in Figure 1.

The repeatability of these results was extremely good, with accurate determination of flow speed and long data samples to provide good spectral estimates. As the model alignment was the only change in test conditions between the two sets of measurements, it was decided to test the sensitivity of the cavity resonance to both the angular alignment (or "pitch" of the model) and the proximity of the cavity to the adjacent tunnel jet shear layer. The latter test was chosen for a number of reasons: it had been suspected that interaction might occur between the cavity resonance and jet shear layer because of some earlier preliminary tests; shear layers in general are very sensitive to sound; and a change in the angular alignment of the model also displaced the model in the y-direction toward the adjacent shear layer (Figure 1). As a final check, the alignment sensitivity test was repeated in the RMIT Industrial Wind Tunnel, a closed circuit wind tunnel with a 2m x 3m enclosed test section and thus no jet shear layers. In the alignment tests, the model was rotated through θ = ±2.0°, while in the proximity tests the model was moved through Y = 0 - 12 mm.

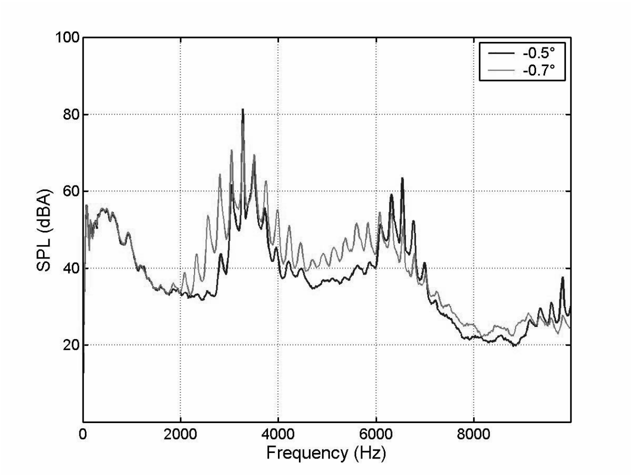

Figure 2. Power spectra showing cavity resonance at different model alignments; θ = -0.5° and -0.7°. The flow speed is 36.7 m/s.

Experimental Set-up

Small Aeroacoustic Open-Jet Wind Tunnel

The majority of the experiments were carried out with the aeroacoustic open-jet wind tunnel detailed in [2], with a nozzle exit area of 0.02 m^2 and an aspect ratio of 4:1. The maximum flow speed was 46 m/s at the nozzle exit, with a nozzle exit turbulence intensity of 0.2% - 0.5%. The mean velocity variation within the jet core, in a transverse plane 10 mm from the nozzle exit, was less than 1%. The total pressure along the centreline of the jet core, adjacent to the model and cavity, was measured with downstream (or axial) distance from the nozzle exit. It was found to fall less than 1% over the region covering the entire cavity and for more than 10 cavity lengths downstream. These conditions gave smooth, well-defined flow over the entire region of the cavity opening and most of the flat plate in which the cavity was situated.

Cavity & Flat Plate Model

In order to minimise the possibility of flow separation at the point where the leading edge or forebody joined the aluminium block containing the cavity, and to provide good boundary layer attributes, the leading edge was designed with a super-elliptic profile, Narasimha & Prasad [3]. All sections of the model were flush to within 50µm with any adjacent sections. The model was situated off-centre, 16.5 mm to one side of the jet centreline, as indicated in Figure 1(b). This position was designated as the origin of the y-axis, Y = 0 mm, and enabled the model to be situated in the core flow of the jet.

The alignment sensitivity tests determined the sensitivity of the resonance mechanism to the pitch of the flat plate, θ, where pitch refers to rotation of the plate about a local z-axis. The shear layer proximity tests involved moving the model progressively in the positive y-direction towards the jet shear layer on the cavity side of the plate. The position guides shown in Figure 1 were permanently fixed to the table on which the model sat and provided a datum from which all measurements of the model position were made. When the model base was situated flush against the position guides, Y was 0 mm and θ was 0°, and as such are defined relative to the position guides and not the tunnel flow.

The cavity used for preliminary tests was relatively large. It had a length (L) of 12.2 mm, a length-to-depth ratio (L/D) of 1, and a span-to-length ratio (W/L) of 5. It was situated 73.5 mm from the leading edge (LE) of the flat plate, at the end of the shaped forebody. The boundary layer profile immediately upstream of the cavity was laminar and, when measured with the plate at θ = -0.7°, had a shape factor of between 2.6 and 2.8. It should be noted here that this plate position is probably at a slight negative angle to the flow, with a small adverse pressure gradient on the cavity side of the plate. The boundary layer profile showed good agreement with the Blasius exact solution for a laminar boundary layer. Transition occurred some distance downstream of the test cavity at a relatively low Reynolds number of 3 x 10^5, probably due to the small adverse pressure gradient mentioned above.

Two flow speeds of 36.7 and 46.0 m/s were used. The respective Reynolds numbers, based on the momentum thickness of the boundary layer at the cavity LE, were 281 and 311. The boundary layer thickness (δ) at this point was 0.87 mm and 0.78 mm, giving an L/δ ratio of 14 and 16 respectively. These parameters would all change slightly with changing θ as either small adverse or small favourable pressure gradients affect the boundary layer characteristics. The two flow speeds were principally chosen because the unusual character of the resonance peaks was not observed at lower flow speeds and was worse at higher flow speeds.

The flow speed was measured using a flattened pitot tube, (height 0.4 mm), 10 mm away from the model surface and approximately 1 mm upstream of the cavity LE. The pressure sensed by the tube was measured using a Honeywell DCAL 410DN 2.5 kPA pressure transducer, with an estimated total error of 0.4 - 0.6% in velocity. Tests indicated that the presence of the pitot tube did not noticeably change the resonance sound spectra and all test cases were performed with the pitot tube in this position.

Large Closed-Circuit Wind Tunnel

The second alignment sensitivity test was performed in the RMIT Industrial Wind Tunnel. This is a closed circuit tunnel with a 9 m long test section and a cross sectional area of 6 m^2. The test section is a reverberant environment but has the advantage of no free jet shear layers. The cavity and flat plate model were situated on the floor 4.5 m from the start of the test section, parallel to and about 1.2 m from the tunnel wall on the cavity side. The tunnel boundary layer at this point was estimated to be 65 mm thick and located far below the level of the cavity.

A reference pitot-static tube at the start of the test section was used to determine the flow speed. The dynamic pressure sensed by this tube was measured with an MKS Baratron Type 398 differential sensor with an estimated total error in velocity of less than 0.2%, but errors due to the distance of the model from the reference tube were of the order of 1%.

As this tunnel was not specifically designed for low noise applications, the background noise was considerable compared to the small aeroacoustic tunnel. In order to facilitate detection of the resonance peaks from the background noise, each test condition was recorded twice; once with the cavity taped over, thus preventing any feedback resonance; and once with the cavity open, as in all other tests. The spectra for the latter case were subtracted from the spectra from the former, thus removing the tunnel background noise.

Sound Measurements & Processing

During all tests a B&K Precision Sound Level Meter with an ½" microphone was used to record the sound. The microphone was positioned 1 metre from the cavity in the aeroacoustic tunnel plenum chamber and 1.2 metres from the cavity in the Industrial Wind Tunnel. In both cases, the microphone was at the same height as the cavity on an X-Z plane passing through the cavity centre (with the model in the $\theta = 0°$ position). In the Industrial Wind Tunnel (a closed circuit test section), the microphone was mounted slightly underflush in a hole in the tunnel wall. In all tests, whenever the model was rotated or translated, the distance to the microphone would change (maximum 1.2%), thus slightly affecting the amplitudes in the recorded spectra. This was acceptable, as the main interest was in the frequency content of the resonance and not the resonance amplitudes.

The sound level meter was calibrated using a RION 94 dB 1 kHz calibrator and all samples were recorded with an applied A-weighting. The use of an A-weighting effectively filtered out the high level, low frequency sound that was of no interest in these tests, and thus improved the effective resolution of the digitised signal. The recorded sound spectra were downloaded to PC using a SONY PC216A digital audio tape recorder (DAT) and its real-time data transfer system, PCIF 250EP. The DAT digitised and appropriately anti-alias filtered the data for a sampling frequency of 48 kHz. The data were subsequently processed with a commercial software package, MATLAB™, with a purpose-written routine (by the first author) that used Welch's averaged periodogram method and appropriate scaling (including calibration) to present the spectra in dBA. Each time-averaged spectrum was produced by analysing a 20 second sample of the recorded sound, using a Hanning window weighting, 50% overlap and 4096 point blocks. This resulted in a total of 467 averages per 20 second sample with an effective bandwidth of 18 Hz and a standard deviation of the spectral estimates of ±0.1 dB.

Results & Discussion

Figures 3 & 4 show the results from the alignment sensitivity and shear layer proximity tests performed with the small aeroacoustic tunnel. As the 46.0 m/s tests showed similar trends and characteristics, only the results for 36.7 m/s are shown here.

In Figure 3, at θ=-1.5° the resonance does not have sufficient energy and no clear resonance peak is visible. At angles greater than -1° the resonance peak is very broad with multiple regularly spaced secondary peaks spread over the main peak. As θ tends towards 0°, the resonance peak becomes narrower, its overall amplitude increases and the number of secondary peaks is progressively reduced. Around 0° the resonance peak suddenly jumps to a different frequency. The precursor to this can be seen in the small peak at ~4.5 kHz which first appears in the -0.5° case and slowly grows until the frequency shift occurs around 0°. For positive θ the secondary peaks disappear (although the processing bandwidth might obscure closely spaced peaks), and the main peaks finally appear narrow and sharp. This final state is the one that is usually shown in the literature for feedback resonance.

The shear layer proximity test showed a similar progression to that of the alignment sensitivity test and so Figure 4 shows a comparison between these two tests. For each of the alignment cases in Figure 4, the data label shows the equivalent displacement in the y-direction due to the rotation of the model against the position guides. From this it can be seen that the shear layer proximity and alignment sensitivity cases show strong similarities. Figures 3 and 4 also illustrate the high sensitivity of the resonance mechanism to even small changes in model position. With the 0°/0.0 mm case on the verge of the sudden frequency jump, some tests showed it to have already jumped, while in others it had not.

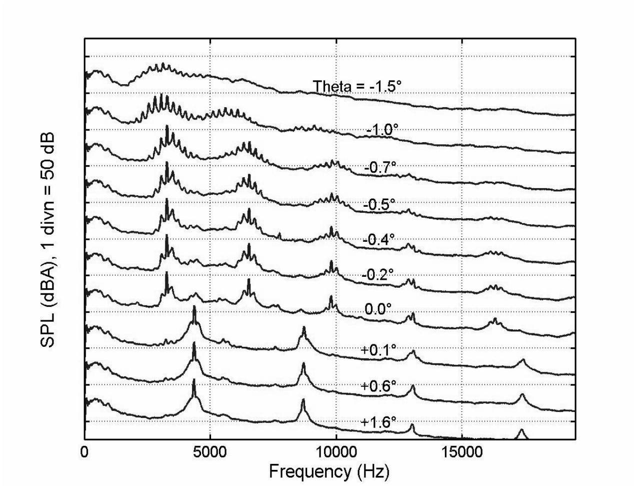

Figure 3. Power spectra of cavity sound for different model alignments in the aeroacoustic wind tunnel at 36.7 m/s. The y-axis is a relative scale only - cases are offset for clarity.

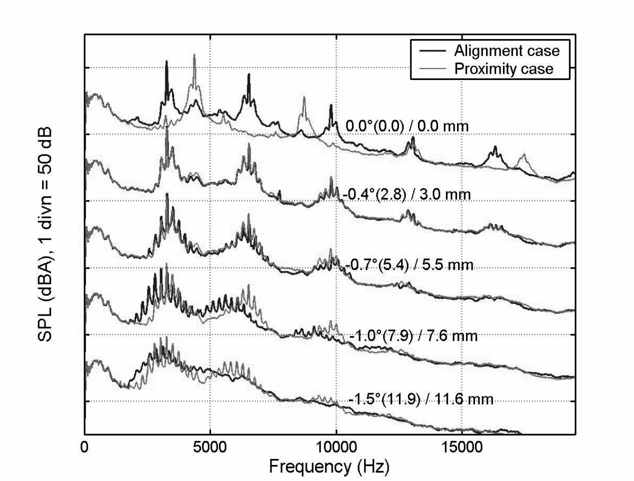

Figure 4. Power spectra of cavity sound showing model alignment compared to shear layer proximity tests in the aeroacoustic wind tunnel at 36.7 m/s. The y-axis is a relative scale only - cases are offset for clarity. Notes on plot indicate: (equivalent Y, mm) / shear layer proximity Y.

If the free jet shear layer is in fact influencing the cavity resonance due to its proximity, then a suitable non-dimensionalised parameter might be the distance from the cavity to the jet shear layer in the y-direction, d, normalised by the momentum thickness of the tunnel jet at the nozzle exit, θ_{je}. For 36.7 and 46.0 m/s, the resonance becomes narrow and sharp at d/θ_{je} of 31 (Figure 4, 0°) and 33 respectively.

The results for the alignment sensitivity case in the Industrial Wind Tunnel, Figure 5, show no such sensitivity to model alignment. Although it must be cautioned that due to the high level of background noise in this tunnel, only 12-16 dB of the main resonance peak is visible as opposed to nearly 50 dB of the peak in the small aeroacoustic tunnel tests. This means that none of the higher mode peaks are visible, apart from a slight bump at ~9.1 kHz (see arrow). The main peak seems very stable and increases slowly in amplitude as negative θ approaches 0°. There is no sign of the secondary peaks seen in the aeroacoustic tunnel tests. Had they been a feature of the cavity resonance, it is expected that they would have been evident within 5 - 10 dB of the main resonance peak. At negative θ there is also a small peak occurring around 3.4 kHz (see arrow) that may correspond to the main resonance peak at negative θ seen in the aeroacoustic tunnel cases, but as it is only ~2 dB above the background noise it is not possible to draw any conclusions.

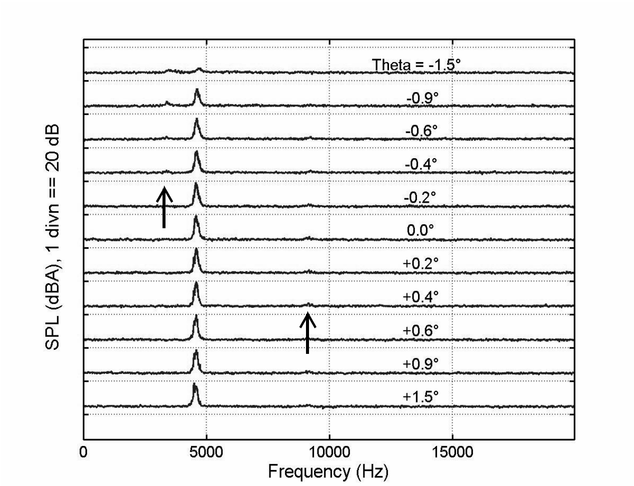

Figure 5. Power spectra of cavity sound for different model alignments in the Industrial Wind Tunnel at ~37 m/s. The y-axis is a relative scale only - cases are offset for clarity.

Figures 3, 4 and 5 would seem to indicate that in fact the feedback resonance mechanism is relatively insensitive to the pitch, θ of the flat plate. Associated with the rotation of the plate in this manner is a slight adverse or favourable pressure gradient over the cavity depending on the direction of rotation. Sarohia [6] used some different forebody shapes in his tests and showed no noticeable effects due to pressure gradient, although the geometry of his models would suggest that the cavity would only have experienced variations from zero pressure gradient to a slight favourable pressure gradient.

The results also indicate that proximity to the jet free shear layer would seem to play a large role in the frequency shifts, secondary peaks and broadness of the resonance peaks. Having said this, note that this phenomenon does not seem to occur at positive θ, even though the cavity is still displaced towards the jet free shear layer, albeit by a smaller distance than that for negative θ. This is possibly due to the effect of a favourable pressure gradient over the cavity. An adverse pressure gradient would make the boundary layer at the cavity LE slightly thicker and more unstable, and the converse is true for a favourable pressure gradient. As feedback resonance depends strongly on the state of the boundary layer at the cavity LE, a stable, thinner boundary layer will give a higher L/δ ratio and may produce a stronger resonance that is less susceptible to interaction with the adjacent jet shear layer.

It is noticeable in the literature that the phenomenon being discussed in this paper has not been mentioned. In many studies by Rockwell and his group (e.g. Rockwell & Knisely [5]), the boundary layer was subjected to a favourable pressure gradient by deliberately accelerating it upstream of the cavity. The reason given was to maximise the spanwise coherence of the shear layer along the mouth of the cavity and to minimise contamination by the recirculation vortex within the cavity. However, these experiments were conducted in a closed water channel, so the interactions discussed above are absent. On the other hand, Ahuja & Mendoza [1] conducted their tests in air using a 4" wide by 0.5" high wall jet with the cavity only 22 mm from the nozzle exit. The proximity to the nozzle exit in their tests raises the question as to whether the cavity resonance would have driven the free shear layer roll-up, as opposed to the tests presented here, where the free shear layer is at least partly influencing the cavity resonance. Sarohia [6] tested in air with two model configurations: a 2" diameter model in a 6" diameter open jet; and a 6" diameter model in a 2 ft diameter jet. He does not state the position of the models relative to the shear layers or the nozzle exit, and so no conclusions can be drawn from his set-up. In general, data published in the literature has been generated from tests in water tunnels, closed circuit wind tunnels, or much larger open jets than that used for the tests detailed here.

Conclusion

An investigation of the spectral quality of feedback resonance in a cavity has shown that the proximity of the cavity to the adjacent test facility free jet shear layer has led to broad resonance peaks, shifted in frequency, and multiple secondary peaks on the main resonance peak. This suggests that an interaction occurs between the cavity resonance and the free shear layer. It was found that model alignment, and hence slight pressure gradients over the cavity, do not have a significant effect on the cavity resonance itself, other than to make it more or less susceptible to other interaction mechanisms. Increasing the distance between the cavity and jet shear layer, and/or inducing a slight favourable pressure gradient in the boundary layer before the cavity, appears to remove the above attributes and produce clean, narrow resonance peaks as commonly seen in the literature for feedback resonance. Further investigation of this phenomenon is definitely warranted, although for the purposes of conducting a study into other aspects of feedback resonance, the production of clean, uncontaminated resonance can be achieved by the above measures.

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