AEROACOUSTIC NOISE AND THE MOTOR VEHICLE: RESEARCH AT RMIT UNIVERSITY

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ABSTRACT: With every new model of car, customers expect reductions in noise and increases in refinement. Aeroacoustic noise plays a significant role in reducing the perception of quality of a vehicle and thus vehicle manufacturers now place a high priority on reducing this noise. In this paper, an overview of the common aeroacoustic noise sources in vehicles, and the research being conducted at RMIT University to better understand and reduce aeroacoustic noise, is discussed.

1. INTRODUCTION

The automotive consumer now has a wide choice of potential vehicles and the sound "quality" of the vehicle plays an increasingly important role in vehicle selection. Because of this, vehicle manufacturers now place considerable emphasis on the customer perception of quality. In car companies, the majority of work is performed for in-cabin sound quality and whilst this can extend to the opening and closing noises of components such as switches and doors, the overall sound quality under typical driving conditions is also important. Due to the efforts of the passenger vehicle manufacturers, levels of noise, vibration and harshness (NVH) have been reduced for car mechanical components (engines, drivetrains and exhausts for example), such that aerodynamically generated noise and vibration is now very significant. A good overview can be found in George and Callister [1].

In Australia, car manufacturers have dedicated noise-and-vibration groups and there are considerable experimental and analytical strengths in Universities. The purpose of this paper is to give a broad overview of aerodynamically generated noise relevant to cars, detailing some of the mechanisms that generate noise, and to give insight into the work that is ongoing at RMIT University.

2. MECHANISMS THAT GENERATE WIND NOISE

Aerodynamically generated noise can be produced by a range of different mechanisms. For the relatively low speed, incompressible flows around road vehicles the main mechanisms are:

- Aspiration noise, caused by the leakage of air in or out of the cabin
- Separated flows that impinge on surfaces, examples of which include the reattaching flow around the A-Pillars and the wakes of mirrors
- Cavity-induced noise, with coupling between the cavity fluid or structure and the exterior flow (Helmholtz resonance for example)
- Vortex shedding from bluff bodies, attached to the (relatively streamlined) body of the vehicle

The resulting noises depend not only on the mechanisms, but are also very dependent on the relative air velocity, which can include the effect of yaw angle (the angle between the apparent wind, as perceived by the moving vehicle, and the vehicle centreline). Since the relative velocity experienced by a moving vehicle is the vector difference of the wind speed (relative to the ground surface) and the road speed of the vehicle, the gusts in the atmosphere help generate wind noises that sound intermittent (for details, see Watkins [2]).

2.1 Aspiration Noise

Aspiration noise is usually insignificant for a well-sealed car. However, due to the pressure differences that exist around the moving vehicle (which, in strong crosswinds, can vary considerably with time) and dynamic body flex (due to road inputs), movement of door seals can still occur and in some cases can permit a leakage through a seal. When this occurs, significant, short-term noise can be generated. Car companies now place considerable emphasis on maintaining effective sealing of the body under the wide spectrum of operating conditions.

2.2 Separated Flow Noise

Much of the aerodynamically generated noise that reaches the ears of vehicle occupants comes from the surface pressure fluctuations arising from a separated vortical flow that originates from either side of the base of the A-pillars (note: the A-pillars are the inclined joining members between the edges of the windscreen and the side windows). For many car shapes, the local flow breaks away from the surface as it tries to turn around the A-pillars and the intermittency and reattachment of the flow to the side window can generate a broadband wind noise. For a given relative velocity, the strength of these vortices (and hence the noise) depends on the yaw angle, which in itself depends on the strength and orientation of the atmospheric wind (see Figure 1 for sample noise spectra, from within a car, at positive and negative yaw angles). When yawed, the leeward side vortex is of greater size and strength than the windward side vortex and therefore, the noise on the leeside is generally greater than the windward side because of this effect. Many studies of the A-pillar flow have been made (Watanabe *et al* [3] for example) and much commercial work is carried out in the early development stages of new car models. Figures 2 and 3 show the difference in flows for yaw angles of ±15 degrees. For the windward side (+15 degrees) the vortex has disappeared and thus the flow is attached and steady, whereas for the leeward side (-15 degrees) the flow is separated and very unsteady, as shown by the somewhat random direction of the wool tufts.

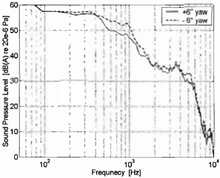

Figure 1: Sample noise spectra at 100 km/h, ±6° yaw

Figure 2: Flow on the side window at +15° yaw (from Watkins and Oswald [8])

Figure 3: Flow on the side window at -15° yaw (from Watkins and Oswald [8])

2.3 Cavity Noise

Cavities come in many shapes and sizes and exist in many areas of a production vehicle. Examples include door and panel gaps, open sunroofs, open windows and wheel arches. For applications that are specific to vehicles, George [1] has identified two general types of noise associated with cavities: a broadband noise that results from both the leading and trailing edges of the cavity; and tonal noise. The types of tonal cavity noise produced by different configurations and the variation in frequency of the noise have been discussed in a review by Rockwell and Naudascher [4]. Tones can be due to a number of feedback mechanisms. These mechanisms can be confined to the cavity shear layer while others involve the cavity volume and/or structure to generate tonal noises. Tonal noise mechanisms confined to the shear layer have a resonance frequency that is a function of freestream velocity over the cavity, while their amplitude depends on cavity edge geometry and shear layer properties. Feedback resonance and shear layer tones are an example of this type of mechanism. Mechanisms that involve the cavity volume or structure have resonance frequencies that are independent of freestream velocity but dependent on cavity geometry. The amplitude of these mechanisms is dependent on the shear layer properties, freestream velocity and cavity geometry. A good example of this type of mechanism is Helmholtz resonance.

Much research has been published on aspects of tonal noise production mechanisms but most studies have been focused on cavity and flow scales pertinent to aircraft; there is a shortage of published data relevant to automotive cavity and flow scales. Experimental and theoretical research is continuing into the parameters that affect some types of cavity noise (Ahuja and Mendoza [5], Milbank *et al* [6] and Howe [7]), with a view to better understanding the mechanisms and ways of reducing tonal noise.

2.4 Vortex Noise

Two and three-dimensional bluff bodies tend to periodically shed vortices. Hence, the vehicle itself sheds vortices; vortices are shed from the rear end of the vehicle, where the flow separates, and from around the A-pillars. Vortices are also shed from protuberances on the vehicle. These include aerials, roof-rack bars, and external rear-view mirrors and a consideration of these and the associated flow field has been given in Watkins and Oswald [8].

Vortex shedding gives rise to fluctuating forces on the bodies in both along and crosswind directions, and thus generates aerodynamically induced noise. The primary frequency of the noise generated is at the vortex shedding frequency, with some minor harmonics. For very low frequencies, the vortices tend to modulate higher frequency noise that may be present. The Strouhal number, S, defines the frequency of vortex shedding and hence noise; $S = fD/U$ where f is the vortex shedding frequency (Hz), U is the freestream velocity (m/s) and D is the body diameter (m). For the range of flows encountered by add ons to the car (both circular and prismatic, such as aerials and roof racks respectively), the Strouhal number can be considered essentially constant with velocity—typical values are from 0.20 to 0.28, depending on the body shape. Further details can be found in texts dedicated to flow-induced noise and vibration, such as Blake [9] and Blevins [10]. Vortex shedding from a vehicle body is more complex and not completely understood. However, researchers have tended to use the vehicle width as the characteristic diameter, as this typically produces Strouhal numbers in the same range as quoted above (see Nguyen [11] for further details).

An example of vortex shedding noise is that emanating from circular, telescopic aerials. Shown in Figure 4 is a standard telescopic aerial, adjacent to an aerial that has been manufactured from a tapered stainless steel blank into which has been ground an optimised spiral grind. Changing the circular sections into a shape that suppresses coherent vortex shedding along the axis leads to a large reduction in the radiated noise. Figures 5 and 6 depict the resulting noise spectrum and the reduction in the peaks in the spectrum can be clearly seen.

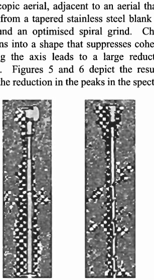

Figure 4: Standard telescopic aerial and optimised spiral ground aerial (both from Czydel [12])

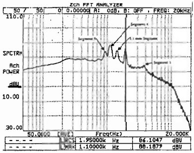

Figure 5: Noise spectrum from a standard telescopic aerial (from Czydel [12])

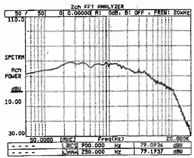

Figure 6: Noise spectrum from a spiral ground aerial (from Czydel [12])

3. CURRENT RESEARCH PROGRAMS AND FACILITIES AT RMIT UNIVERSITY

Despite producing less than 1% of the world's vehicles, Australia is well served in respect of facilities and undertakes research that is of international significance. Australia's largest vehicle aerodynamics and aeroacoustics research group is located at RMIT. An overview of the major infrastructure and research programs at RMIT is given here.

3.1 Experimental Facilities

There are two relatively quiet tunnels in Australia that can accept full-size cars—the Monash University 1 MW tunnel and the RMIT University Tunnel. The Monash Tunnel is an open-jet tunnel (i.e. it does not have solid boundaries close to the vehicle, instead the vehicle is immersed in a jet that issues into a plenum chamber). In contrast, the RMIT Tunnel is of the traditional type, where the test section is enclosed by walls and a roof. As part of a recent refurbishment, acoustically treated turning vanes were installed. A plan view of the RMIT tunnel is shown in Figure 7. Car and component companies use both of these wind tunnels for commercial and research work, often in conjunction with postgraduate research students.

In addition to the major infrastructure, instrumentation includes: a Head Acoustics Aachen binaural head system (which can be seen in the car in Figures 3 and 8); SPL meters; multi-channel DAT recorders; and an ellipsoidal, dish-type, highly directional microphone of 1m diameter.

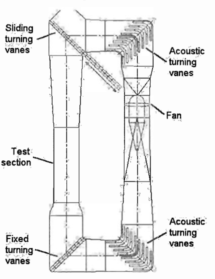

Figure 7: Plan view of the RMIT University Wind Tunnel

3.2 Current Research Programs

As well as commercial development programs that are undertaken by the car and component companies, there are several basic research programs sponsored by the car companies and by the Australian Government (via the Australian Research Council), including an investigation of the intermittency of in-cabin wind noise. As vehicle occupants notice noise sources that fluctuate in amplitude more than noises of constant amplitude, it is important that sources of fluctuating noise be investigated during a vehicle development program. However, aeroacoustic noise sources often fluctuate in amplitude because of fluctuations in the atmospheric wind, but the wind tunnels used to evaluate wind noise generally feature very smooth airflow. Hence, noise fluctuations generally do not occur and cannot be evaluated in these wind tunnels. To address this, a program to better understand the noise fluctuations is being undertaken, with the hope that results from this program can be used to develop a system that allows fluctuations to be 'added' to noise measured in a wind tunnel. The main aim is to be able to synthesise on-road noise from noise measured in a wind tunnel so that it includes some of the fluctuations that are experienced on-road. It is also expected that tyre noise and mechanical noise could be added to the wind noise measured in a wind tunnel, giving engineers a more realistic prediction of the noises that will be present when a new vehicle is driven on the road through "real" atmospheric winds.

To investigate the links between fluctuations in the atmospheric wind and modulation of sounds heard within the vehicle cabin, velocities around the passenger-side A-pillar were measured simultaneously with the noise inside the cabin during a comprehensive series of tests performed on-road and in the wind tunnel. Velocity measurements were performed with 4-hole, 'Cobra' pressure probes that allow determination of the velocity in 3-components, and fluctuations of velocity of up to 1500 Hz to be measured (which is well in excess of the frequency of the major fluctuations in the atmosphere, which are typically less than 10Hz). The noise measurements were performed with an Aachen binaural head system, which is shown in Figure 8 along with two Cobra probes (one upstream of the A-pillar and one next to the side window).

Figure 9 shows a sample section of data that illustrates a link between wind velocity fluctuations and interior noise fluctuations. The top time trace shows the wind velocity, with the mean removed, while the centre time trace shows the local yaw angle, also with the mean removed. The bottom time trace shows a representation of interior noise fluctuation, which has undergone signal processing to emphasise the fluctuations. Strong correlation between the velocity and noise signals is observed, and the coherence for low frequency (less than 8 Hz) fluctuations is found to be above 0.8. This, and other similar, data have been used to synthesise noise in windy conditions from wind tunnel data with encouraging results.

Data from on-road testing are also being processed to separate and provide information about wind noise, mechanical (mainly transmission) noise and tyre noise — in practice this proves difficult, as all three noise sources overlap in terms of frequency content and while the mechanical noise is relatively constant, both the wind noise and the tyre noise fluctuate with time.

Figure 8: Set-up for wind tunnel and on-road testing, showing two Cobra probes and an Aachen head

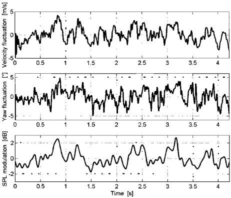

Figure 9: Sample link between velocity and yaw angle fluctuations and modulation of the sound pressure level

In addition to the programs that involve direct measurement of sound and velocity, work is ongoing on the reduction of surface pressure fluctuations near the A-pillar. Whilst the hydrodynamic pressure fluctuations can be a direct cause of noise, another way that sound is generated in the car cabin is by the surface pressure fluctuations exciting the car structure, particularly the side window glass. In order to reduce this, an increase of the A-pillar radius is required. To assess the influence of size and shape of curvature, and to ascertain how useful scale models are in the very early stage of car development, a comprehensive program of tests measuring the surface pressure fluctuations in the A-pillar region are being carried out (Alam [13]). In Figure 10, two very different geometries of A-pillar can be seen and the influence on the surface flow is depicted using wool tufts. Additionally, microphones have been flush-mounted at various locations on the surface in order to measure fluctuations in surface pressure. These pressure fluctuations are non-dimensionalised by the reference dynamic pressure, to give Cp_{rms}. The variation in Cp_{rms} for various radii of A-pillar can be seen in Figure 11. It is seen that radii tighter than 0.3m lead to a significant increase in the surface pressure fluctuations, particularly on the leeward (negative yaw) side. All of these measurements are also compared with similar work carried out on production cars, in both the wind tunnels described above and on-road, with a view to determining scaling laws for aerodynamic noise between model scale and full-scale testing.

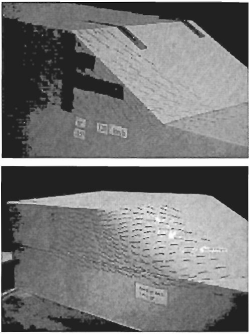

Figure 10: Comparing the influence of A-Pillar radius on the flow and pressure fluctuations (both from Alam [13])

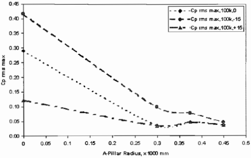

Figure 11: Fluctuating Cp rms Variation with Local A-Pillar Radii, Yaw = -15°, 0° and +15°

FUTURE DIRECTIONS

The preceding discussion has given an overview of automotive aeroacoustic noise sources and the recent research work conducted at RMIT to better understand these noise sources. Work is ongoing in all of the areas discussed and new areas are starting to be investigated, with the aim of providing vehicle manufacturers with more powerful design and analysis tools for the prototype and development stages of a new motor vehicle.

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