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Automotive Aeroacoustics: An Overview

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Abstract

Vehicle aeroacoustic performance has a strong influence on customer perception and also has importance for safety and comfort. Wind noise performance was once differentiated by the quality of sealing. Today, achieving competitive wind noise performance also depends on minimising aeroacoustic noise sources generated by the vehicle form, and on attenuation in the noise pathway from sources on the exterior to the vehicle interior. Attenuation in the noise pathway from sources on the exterior to the vehicle interior, especially through glazed surfaces, will continue to play an important role in controlling cabin noise, with a particular emphasis on achieving attenuation efficiently in terms of component mass. The human brain is not only sensitive towards the level of steady broadband noise, but distinctive features such as tonality or modulation draw the attention of the vehicle occupant and impact negatively on perception. Complex indices are often required to define good wind noise performance. This includes the consideration of multiple frequency bands and effects of the range of yaw angles experienced on-road. A key to achieving future vehicle refinement is bringing together an understanding of unsteady onset flow conditions, their impact on cabin sound pressure level and modulation and in turn the impact of noise level and modulation on psychoacoustic perception.

Keywords

aeroacoustics, acoustics, passenger vehicles, turbulence, unsteady flow, vehicle aerodynamics, vehicle comfort, vehicle noise and vibration, wind noise

Introduction

The relative contribution of the engine, powertrain, wheels and wind in producing the overall noise heard inside the passenger compartment of a car varies at different vehicle speeds. At higher speeds generally above 100 kph, such as those experienced during highway driving, aerodynamic noise tends to dominate. Aeroacoustic sources in areas near to the vehicle occupants, such as around the front side glass, can lead to wind noise being a prominent source of noise. The reduction of this interior cabin noise is desirable, enhancing both the level of passenger comfort inside the vehicle and the perception of the vehicle's quality. Importantly, wind noise can also be significant in road safety, since high levels of noise can lead to driver fatigue and a reduction in concentration. The importance of this is highlighted in the J. D. Power customer satisfaction rankings, where wind noise has been the top complaint every year between 1987 and 2014, with infotainment issues only recently becoming higher[1].

This paper provides an overview of automotive aeroacoustics and focuses on physical phenomena and their implications in an automotive context rather than specifically reviewing tools used by the development engineer, which have been covered by other authors[2;3]. It considers the fundamentals of wind noise and its influence on passenger perception. The paper seeks to discuss what was and is required to achieve competitive aeroacoustic performance from the perspective of automotive development and aims to point the way for the future.

Acoustic Characterisation

Sound Pressure and Sound Pressure Level

Sound pressure is the local pressure deviation from the ambient pressure due to acoustic wave propagation. The SI unit of sound pressure is the pascal (Pa). Owing to the wide range of hearing sensitivity spanning a number of orders of magnitude, from approximately 2×10^{-5} Pa (approximate threshold of hearing) to up to 2×10^{2} Pa (threshold of pain), the logarithmic sound pressure level (SPL) is commonly used. This is expressed as a ratio of the RMS pressure P to the reference pressure $P_0 = 2 \times 10^{-5}$ Pa of the threshold of hearing and measured in decibels (dB), with the definition given by:

$$\mathrm{SPL} = 10 \log \left(\frac{P_{\mathrm{RMS}}^2}{P_0^2} \right) = 20 \log \left(\frac{P_{\mathrm{RMS}}}{P_0} \right). \qquad (1)$$

When combining the contributions of multiple sound sources, it should be noted that since SPL is measured logarithmically, the levels of individual sources do not combine linearly. For broadband incoherent sources, such as the noise heard inside the cabin of a vehicle, the sound pressures (not sound pressure levels) sum in a linear fashion.

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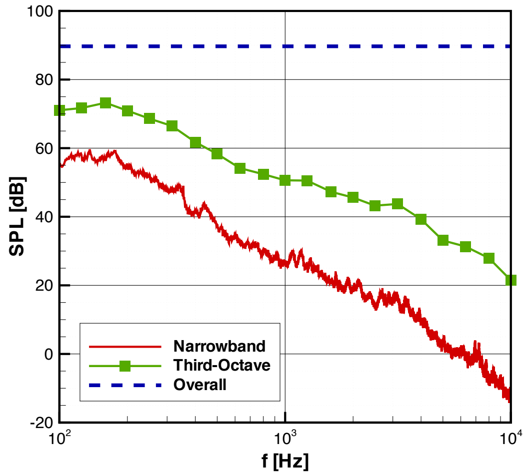

Figure 1. Comparison of overall level, third-octave and narrowband spectra

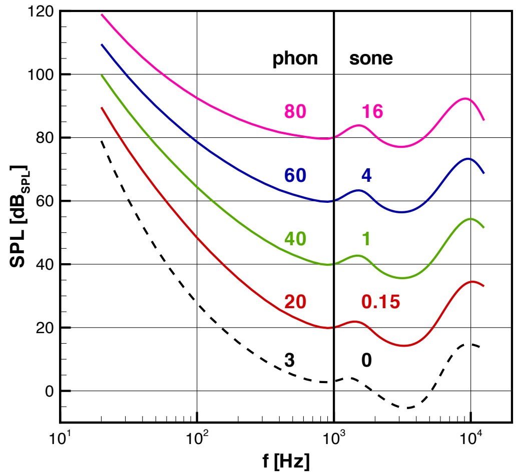

Figure 2. Equal loudness contours according to ISO226:2003

For tonal sounds, phase information is important since it can lead to cancellation, but for broadband noise phase information can be ignored.

Spectral Content of Sounds

Characterising a particular noise by SPL alone can hide much of the nature of the sound. The ability to look at the spectral content of a sound provides a greater insight into not only how the sound may be heard, but also some information as to the nature of the sound sources. By taking a Fast Fourier Transform (FFT) of the sampled sound data, the spectral content can be revealed. The resulting narrowband spectrum has a frequency resolution equal to the ratio of the sampling frequency of the signal to the number of samples used to calculate the FFT.

Whilst the narrowband spectrum provides the most detailed spectral record of a particular sound, for many applications, dividing the spectrum into a series of coarser octave bands (and fractions thereof) can often be more convenient. One octave is a doubling of frequency, for instance a frequency of 2 kHz is one octave higher than 1 kHz, with 4 kHz an octave beyond.

Figure 1 compares the overall SPL, third-octave and narrowband spectra for the same sound. To extract the third-octave spectrum from the narrowband spectrum, the spectral content falling within each third-octave frequency band is combined. The same process is used when determining the overall SPL, where the overall spectral content over the entire recorded frequency range is combined. This has the implication that spectra with a coarser frequency resolution appear to have a larger SPL than data of a finer frequency resolution. Therefore care must be taken when comparing data of differing spectral resolution. An advantage of third-octave spectra is that the frequency bands are commonly defined, allowing a consistent comparison between different data without the need to specify a narrowband frequency resolution.

For tonal sounds, the narrowband spectra can be more appropriate. The relatively coarse frequency bands of a third-octave spectrum can spread the tonal spikes present in a narrowband spectrum over the width of a third-octave band, leading to a reduction in definition of the particular frequency of the tone. In some cases, this can lead to tonal spikes becoming lost in the overall spectrum. In the case of a narrowband spectrum, these can be clearer and provide more detail as to the level and tonal frequency of these sounds.

Psychoacoustics

Psychoacoustics is the study of sound perception, linking acoustics with both the physiological response of how the body receives a sound and the psychological response of how the received sound is then perceived by the brain. Thus, the study of psychoacoustics is an attempt at quantifying one's perception of noise and is therefore of relevance to the automotive industry to characterise how the sound heard inside a vehicle may be perceived by a passenger.

Loudness. Loudness is one psychoacoustic parameter describing how the ear perceives the strength of a particular sound. Human hearing sensitivity varies with frequency owing to the transfer function between acoustic waves in the ear to the cochlea. This frequency-dependent sensitivity can be described through use of equal-loudness contours, as shown by Figure 2. These are lines plotting a contour of equal hearing sensation in the frequency domain. Hearing sensitivity is reduced at low frequencies, whilst is at its greatest between 3 and 4 kHz owing to resonances of the auditory canal. These contours were originally defined by work undertaken by Fletcher and Munson[4] and further revised[5], forming the basis of the original ISO standard[6]. This standard was later revised into its current form[7].

A number of contours are plotted, each intersecting 1 kHz at a different sound pressure level. It is this level, measured in dB, which acts as the reference for the *phon* scale of loudness. This scale is one of the two methods for quantifying the curves. The *sone* scale is a method to linearise the subjective perception of loudness of an acoustic signal. One sone is defined as corresponding to the equal loudness contour that intersects the frequency of 1 kHz at 40 dB. Sounds perceived twice as loud have a loudness of two sones. The dashed line is the contour for the average threshold of human hearing. For vehicles driving at highway

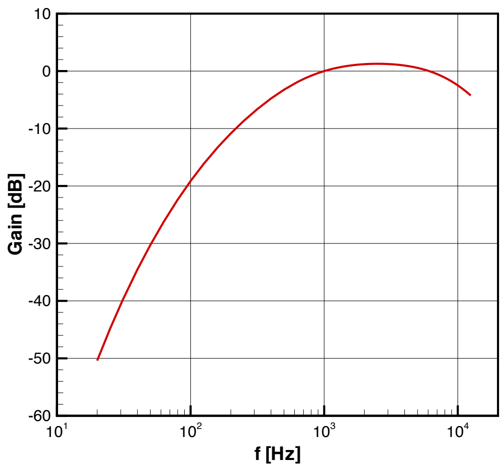

Figure 3. Frequency response of the A-weighted filter

speeds (130 kph), the cabin noise contribution due to wind noise is typically between 15 and 20 sones.

To determine the overall loudness of a particular sound, a number of methods are available. These essentially take the measured sound and combine it with the appropriate equal-loudness contour to determine an overall parameter of loudness. These include the Zwicker model of loudness, forming part of the ISO standard[8]. Moore and Glasberg[9] have since refined these loudness models and this work forms part of the ANSI standard[10].

A-Weighting. Prior to the development of these overall loudness calculation methods, a number of electronic filters were developed to approximate the equal-loudness contours of Fletcher and Munson[4]. These electronic filters were originally designed to be incorporated into sound level meters, so as to provide an overall SPL more representative of how an average person would perceive the level of the sound. Since the profiles of the equal-loudness contours are not constant for different sound levels, a number of filters were designed.

Commonly used is the A-weighted filter, shown in Figure 3, which approximates the equal-loudness contour of 40 phon, or 1 sone. Owing to the limitations in the design of the electronic filter at the time of development, the resonant peaks of the equal-loudness contours are not captured, limiting its accuracy in describing the psychoacoustic response of a vehicle occupant at these frequencies. However, the main advantage of this filter was its simplicity of use, in that a sound level meter can report a weighted overall SPL, with no data processing required. This convenience led to the widespread adoption of the A-weighted sound pressure level measurement, denoted by the unit dB(A).

With the development of modern electronics, the requirements to have a relatively simple filtering circuit have diminished. However, the popularity of the measurement has continued mainly due to its convenience, in spite of the limitations discussed by a number of authors[11].

Other Psychoacoustic Parameters. To assess how much a particular noise affects the intelligibility of speech, the parameter of articulation index (AI) can be used. This is defined in a number of different ways, although each has the same aim in characterising a particular noise using a scale of 0–100%, with 100% as perfect speech intelligibility and 0% where speech is completely masked by the noise.

The concept of articulation index was originally developed to characterise speech intelligibility in the field of communications[12]. Later procedures for computing AI were formalised[13] and formed part of the ANSI standard[14]. The procedure to calculate AI according to the standard was quite involved and this led to an alternative, simpler, method being developed[15;16] oriented towards the automotive industry. This considers frequencies between 200 Hz and 6.3 kHz, with greatest weighting given between 1 and 2 kHz.

A wide range of other psychoacoustic parameters are available, with a number described in the following section[17]. These include parameters to quantify the spectral content of a noise such as sharpness, which is calculated in a similar manner to loudness but placing more emphasis on the higher frequency content of the noise. In automotive aeroacoustics, this is dominated by wind noise, since wind noise sources dominate the higher frequencies[18]. Other parameters include roughness and fluctuation strength that are related and are associated with the temporal fluctuation of a sound signal. Fluctuations at frequencies greater than 10 Hz increase roughness, with those below increasing fluctuation strength. The maximum human sensitivity to fluctuations occurs at 4 Hz with this sensitivity thought to be linked to the average speaking rate of four syllables per second[17]. Since unsteadiness in oncoming wind conditions can lead to fluctuations in the wind noise heard inside the cabin, this highlights the importance of considering the unsteady aeroacoustic response of a vehicle on-road.

Often a single parameter may not be sufficient to characterise the wind noise performance of a vehicle, since there are many aspects covering frequency content, overall level and temporal fluctuations. Jury testing can be used to correlate the quantitative parameter with the qualitative response of a listener. For instance a number of parameters can be assessed to determine those that best characterise a component of wind noise in the overall noise heard inside the cabin, whereby composite indices can be created[19;20], including those that compare the relative importance of wind noise sensitivity to unsteady wind conditions to the overall level of cabin noise[21]. However, many vehicle manufacturers consider the nature of these composite metrics secrets and seldom publish their findings[22], but often include parameters of dB(A), loudness, AI and sharpness, capturing various aspects of how noise affects a customer's experience inside the cabin.

Aeroacoustic Mechanisms

Fundamental Aeroacoustic Sources

There are three principle mechanisms for aeroacoustic noise generation[23;24]. Each of these can be approximated by way of an idealised model. The first mechanism originates from unsteady volumetric flow, such as that emanating from a leak into the cabin of a vehicle, or from the exhaust of a piston engine. This is idealised by a monopole source, which is a fluctuating pressure source, where $P = f(r)$, with r the radial distance from the source. The second mechanism

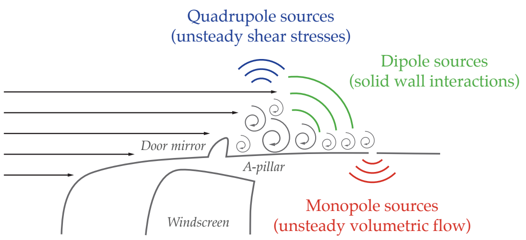

Figure 4. Aeroacoustic sources in the sideglass region, adapted[27]

arises from the interaction of unsteady pressures upon a rigid surface. Von Kármán vortex shedding is an example of this type of acoustic source, where the vortex-induced pressure fluctuations form a dipole sound source on the body surface. This can be modelled using a dipole sound source comprising two adjacent monopole sources oscillating out of phase, where $P = f(r, \theta)$, with θ describing the directional dependence on pressure radiation. The final mechanism is caused by unsteady internal stresses in a fluid (for example in the shear layer at the periphery of a jet) and is modelled by the quadrupole source, which is a combination of two dipole sources, also where $P = f(r, \theta)$. Each of these sound sources scales differently with flow speed u and Mach number M, leading to the following relationships:

$$\begin{aligned} I_{\text{monopole}} &\sim \frac{\rho}{c} u^4 = \rho u^3 M \\ I_{\text{dipole}} &\sim \frac{\rho}{c^3} u^6 = \rho u^3 M^3 \\ I_{\text{quadrupole}} &\sim \frac{\rho}{c^5} u^8 = \rho u^3 M^5. \end{aligned} \tag{2}$$

These show the relationship between flow speed, Mach number and sound intensity I for each source respectively[25;26]. The symbol ρ represents air density and c represents the effective speed of sound. Sound intensity is related to sound pressure when combined with the acoustic particle velocity, describing the sound power per unit area.

At the relatively low speeds that a vehicle travels on the road, where $M < 0.1$ the monopole sound source dominates, followed by the dipole source and quadrupole sources are often neglected in the study of vehicle aeroacoustics. In the absence of leak noise, dipole sources tend to dominate the overall cabin noise of a road vehicle. It is also shown that the sound intensity of such a monopole is proportional to the flow velocity raised to the fourth power, whilst the dipole sound source is proportional to the flow velocity raised to the sixth power. As the most significant aerodynamic noise mechanisms in vehicles are either monopoles or dipoles, experimental observation tends to find that the intensity of this aerodynamic noise increases with flow speed raised to between the fourth and sixth power[2]. Figure 4 shows examples of the three different sound sources in the sideglass region of a vehicle, which is dominated by flow structures around the A-pillar and door mirrors.

By assessing the sensitivity of various exterior and interior noise sources to flow speed, a valuable insight can be gained into the physics of the sound sources[28]. Whilst the overall broadband noise of a vehicle typically scales with u^6, in smaller details these scaling laws can vary and can combine to form a sensitivity made up of a combination of different powers. Therefore, since wind noise is particularly sensitive to wind speed, care must be taken to either keep wind speed constant during wind tunnel tests or recorded when testing on-road. This also implies that local velocity effects due to the body shape of a vehicle can also be extremely significant in the generation of aerodynamic noise. For example, it is not uncommon to have a surface pressure coefficient around the A-pillar of a vehicle of -2 (equivalent to a 170% increase in local flow velocity) resulting in an approximate increase in sound pressure level of 14 dB[29].

Hydrodynamic Fluctuations

Hydrodynamic pressure fluctuations are produced by turbulent flow impacting on a surface, for example a vehicle sideglass as in Figure 4. Locally, these fluctuations are often at a much higher level than the fluctuations of the acoustic field. However, the acoustic field often dominates the contribution measured inside the cabin[30]. A pressure wave fluctuating at a given frequency f, is a function of its wave speed v and wavelength λ as follows:

$$f = \frac{v}{\lambda}. \tag{3}$$

Often this relationship is described in terms of wavenumber k, such that:

$$k = \frac{2\pi f}{v} = \frac{\omega}{v}. \tag{4}$$

The physical scale of hydrodynamic pressure fluctuations at a given frequency depends on the local convection velocity, which is often an order of magnitude slower than the speed of sound in a typical automotive situation. Consequently the wavelengths of the acoustic field are of an order of magnitude longer than the hydrodynamic fluctuations (the acoustic wavenumbers are an order of magnitude smaller). The glazing provides a strong filter for the smaller wavelength, higher wavenumber, hydrodynamic fluctuations since these do not couple as effectively with the structural vibration characteristics of the glass[31].

Owing to its importance as a contribution to the noise inside the cabin it is of interest to be able to measure the exterior acoustic field. However it is a challenge since the acoustic field can be masked by the hydrodynamic pressure fluctuations, and can be referred to a 'pseudo-sound'[30]. Consequently surface or flush-mounted microphones generally are more effective at measuring the hydrodynamic field alone in regions of high turbulence, such as the sideglass. Methods that are available[32] however can suffer from some limitations, for instance spatial resolution, since the acoustic field is not spatially homogeneous[33]. Since the glazing is an effective wavenumber filter, indirect measurements of the acoustic field using accelerometers mounted on the glass can also be used[34].

Typical Vehicle Wind Noise Sources

Historical Background

Early work during the 1960s and 1970s in automotive aeroacoustics separated aerodynamic noise into three principle classifications: broadband wind rush noise, caused through the passage of airflow around the vehicle; tonal noise, caused by sharp edges and gaps in the bodywork; and resonances caused through open windows and sunroofs[35]. Other early work noted that the aerodynamic shape of a vehicle was insignificant in the overall wind noise, whereas small air leaks in critical areas such as the A-pillar region are the principle cause of objectionable wind noise[36] . It was also stated that wind noise could be eliminated through good sealing about the doors and windows.

These conclusions certainly belong to a previous era of aeroacoustic research, although they do emphasise some important points that are still valid today. Firstly, that monopole sound sources caused through aspiration noise can dominate the overall cabin noise if door and window sealing is not optimised. Secondly, since vehicles in the 1960s spent less time cruising at modern-day highway speeds, this highlights that wind noise only tends to dominate the overall cabin noise when the vehicle is travelling sufficiently fast. Finally, over the years leading up to the present, manufacturers have significantly refined and reduced noise from the engine and powertrain, so that today wind noise is much more significant than in the past, even though levels of wind noise are typically half as loud. This continues today, since through the increasingly widespread development of quieter electric and hybrid technologies, and also with automated driving potentially leading to platoons of vehicle travelling at higher speeds on highways, wind noise is set to become more significant still in the overall noise heard by the occupant of a vehicle cabin.

Since flow behaviour and noise generation are inextricably linked, investigations into the flow around areas of a vehicle which are relevant in the production of noise are important in the field of automotive aeroacoustics. For instance, work in the 1970s concluded that aeroacoustic noise is highly dependent on separated flow structures, particularly those of the A-pillar vortex[35;37]. Since both the shape of the body and external features affect separation, a development of this conclusion results in a direct link between vehicle shape and wind noise.

Vehicle Form

This section provides a summary of the range of aerodynamic sound sources typically present on a road vehicle. In the following sections, these are discussed with examples from a number of investigations.

A-Pillar. One area of importance in generating wind noise is the A-pillar region, which is positioned forward of the front doors of the vehicle. This region is an area of flow separation and is near to the ears of the driver and passengers. The A-pillar vortex dominates the flow around the A-pillar and sideglass, as shown in Figure 5.

The noise generated in this region at higher road speeds ($>$ 100 kmh^{-1}) is particularly important[39], with the separated region of the A-pillar vortex producing a much higher sound pressure level than the reattached flow region[40]. The vortex on the leeward side of the vehicle is larger[41] and tends to produce a greater noise[42]. A number of studies have investigated the effect of changing the radius of the A-pillar. Generally, a larger radius reduces the level of noise generation by reducing the size of the separated region[43].

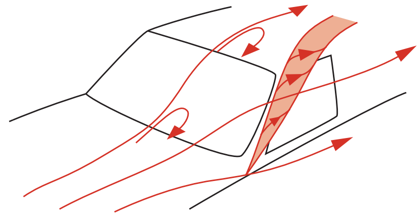

Figure 5. Typical vortex structure around the A-pillar, adapted[24;38]

The effect of increased levels of freestream turbulence on the flow structures around the A-pillar has also been investigated. Increased free stream turbulence with scales relevant to the vehicle boundary layer, reduces the size of the A-pillar vortex[44–46]. The subsequent pressure loading in the region affects door loads and can change the sealing properties of the door. Larger scale flow unsteadiness (eg: as experienced on-road) will tend to increase pressure fluctuations and modulations of wind noise[47–50].

Door Mirrors. Door mirrors tend to be located in a region of high speed turbulent flow and therefore have a high potential for noise generation. An increase in the gap between the mirror body and door can also reduce any local flow acceleration between the mirror body and the vehicle, thus reducing noise. Changing the shape of the mirror head to reduce the size of the mirror wake has been shown to give potential benefits of up to 20 dB, dependent on the original design of the mirror[39;51;52]. Current legislation requires production vehicles to have exterior mirrors, however there are an increasing number of concepts and small-volume production demonstrator vehicles with camera mirror technology potentially providing options for mirror-free vehicles in the future[53].

Tonal mirror noise can be caused either by coherent shedding structures as a result of the flow interacting with the external shape of the mirror, through fluid resonance in the cavity of the mirror body[54], or through instabilities in the fluid boundary layer[55]. For this mechanism, shape changes on the trailing edge of the mirror or tripping the boundary layer to turbulence[56;57] can remove these tonal effects. Bumps and grooves are occasionally placed on mirror bodies and stems[2;27] to break up coherent tonal shedding structures.

Windscreen Wipers. Windscreen wipers are another example of how relatively small changes in geometry can have a large effect on noise generation. Studies have noted that with the windscreen wipers of a vehicle removed, external pressure fluctuations can be reduced by up to 6 dB[39]; it is also possible to design the vehicle so that the wipers are hidden behind the bonnet whilst in a parked position. Also, raising the height of the rear of the bonnet by 10 mm can reduce noise generation by approximately 5 dB[43], particularly affecting frequencies greater than 5 kHz[58], or over a wider frequency range when the vehicle is subject to yawed flow conditions[59;60].

Glazing. Whilst not a noise source itself, glazing provides an important noise path into the cabin. Areas of vehicle body work generally include the outer skin, insulation material and interior lining hence with relatively high acoustic attenuation compared with glazed areas. Further, some glazed areas such as the windshield and front sideglass are subject to high acoustic loading. One method to increase the attenuation of a glazing panel is to increase the mass through an increase in glass thickness. Doubling the panel thickness doubles the mass giving an approximate 6 dB increase in attenuation[61], or more specifically transmission loss, below a frequency known as the coincidence frequency (above this frequency, stiffness controls the transmission loss). This is the frequency where there is a strong coupling between incident acoustic waves and the bending vibrations in a panel, resulting in a reduction in attenuation. The relationship between the coincidence frequency f_c, speed of sound c, panel thickness h and the density ρ_m, Poissons ratio ν and Youngs modulus E of the panel material is shown as follows[62]:

$$f_c = \frac{c^2}{2\pi h}\sqrt{\frac{12\rho_m(1-\nu^2)}{E}}. \tag{5}$$

Since the material density, Poissons ratio and Youngs modulus are properties of the panel material, the combined term hf_c is constant for a given material. For a glass with properties $E = 60$ GPa, $\nu = 0.24$ and $\rho_m = 2400$ kgm^{-3}, the combined term $hf_c = 12.7\text{ms}^{-1}$. For glass thickness ranging from 3 mm to 6 mm, the corresponding coincidence frequencies range from 4.2 kHz to 2.1 kHz.

Often, the increase in vehicle mass to reduce noise levels may be unacceptable to a vehicle manufacturer, since this can lead to increases in fuel consumption and consequently emissions. An alternative to achieve noise targets is to incorporate a laminate polymer interlayer between two glass panels. The additional damping provided by the laminated construction has the effect of reducing the dip in transmission loss around the coincidence frequency. An example of this is shown in Figure 6, comparing the transmission loss of a single glass panel (monolithic) with that containing a 0.76 mm polymer interlayer[63], where the coincidence dip can be seen.

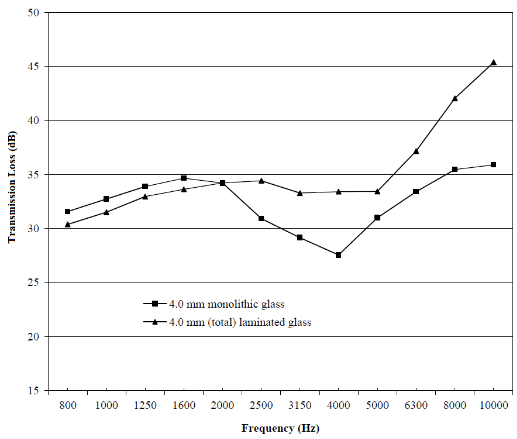

Figure 6. Comparison of the transmission loss of monolithic and laminated glass windows with the same total thickness, adapted[63]

Even relatively modest increases in this frequency range can result in significant subjective improvements in the perceived levels of wind noise in the cabin, since the typical coincidence frequency ranges for glass fall within the same frequency band of loudness sensitivity, as shown by Figure 2.

Since the total thickness of the panels is kept constant in the comparison of Figure 6, the addition of the polymer interlayer consequently reduces the overall mass of the panel, since glass has a higher density than the polymer. This can be seen in the lower frequency region, where the laminated construction has a reduced transmission loss than the original monolithic glass.

A number of different polymer interlayers are available from suppliers, including those specifically designed to improve acoustic attenuation[64]. With increased pressure throughout the automotive industry to reduce weight through thinning glazing further[65], these materials are likely to become more frequently used to maintain the required noise performance inside the cabin.

Underfloor. The underfloor is often the dominant wind noise source at lower frequencies. Components mounted under the vehicle can lead to complex flow structures, potentially exciting resonant modes of the vehicle floor structure, with acoustic modes also being created in cavities. Components such as chin spoilers can have the effect of reducing the level of pressure fluctuations on the floor by diverting the flow away from these regions[66;67], decoupling the flow from potential acoustic generation mechanisms. Small holes in body side-members can also have a significant impact on noise generation[68], resulting in a 5 dB increase at frequencies below 500 Hz in some cases.

Techniques to assess the underfloor contribution experimentally in the wind tunnel generally involve blocking the underfloor region with a full ‘skirt’ to isolate this from the flow, typically used when validating computation approaches[67;69;70].

Other Noise Sources. A range of other aerodynamic noise sources are also present on a vehicle. One source that is relatively simple to mitigate is radio aerial noise, which can be reduced by increasing the angle of the aerial[71], wrapping the cylindrical profile with a helical strake[72] or even removing the necessity for the device entirely.

Roof bars are also commonly known as a noise source on a vehicle, as well as creating additional drag. Designing profiles such that they are irregular and incorporating crenelated strips can reduce coherent vortex shedding and the resultant dipole noise sources[73].

Body Sealing

The sealing system of a vehicle, including seals around the door apertures and glass, can have a significant impact on the overall noise heard inside the cabin. As discussed previously, the noise mechanism from leaks is that of a monopole, which has the highest intensity of all aeroacoustic sources. It is therefore important to make sure that leaks are prevented. Noise of the sealing system tends to lead to higher frequency noise inside the cabin, generally above 500 Hz[74;75].

It is also important that the sealing system is designed such that at higher speeds, sealing of the door and glass is maintained under the increased pressure loading, particularly around the A-pillar region where loads are greatest. Multiple sealing lines can be used to ensure seal integrity, including full rings of sealing on both the door and body. Margin seals can also be added to the exterior of the vehicle, reducing

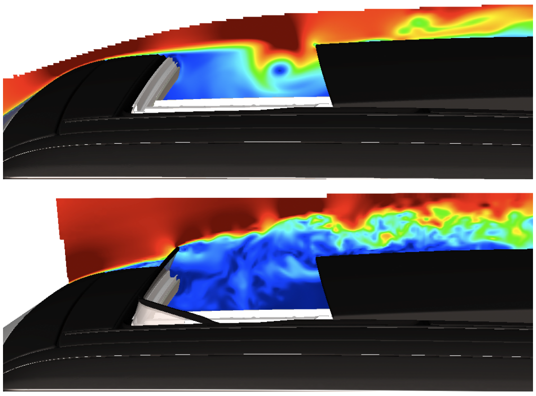

Figure 7. Open sunroof contours of transient velocity magnitude: (top) deflector removed, (bottom) mesh deflector[78]

noise created in panel gaps around doors[76] as described in the following section.

Open Cavities

There are two main sources of cavity noise on a vehicle: noise generated by large cavities such as an open sunroof or windows; and also cavity noise from smaller cavities such as gaps in body panels.

Sunroof and Side Windows. Resonances caused by open windows and sunroofs, is also known as *booming*, *wind throb* or *buffeting*[77]. It occurs when the transient characteristics of the shear layer over the sunroof or rear window opening (Rossiter mode) are able to excite the acoustic Helmholtz mode of the vehicle cabin. This leads to a self-sustained oscillation of the shear layer[78]. Bi-directional coupling takes place between the shear layer and the acoustic response of the cabin leading to a lock-on of the vortices traveling over the sunroof to the resonant frequency of the cabin.

For a sunroof, an upstream deflector is a common approach to prevent boom[75;78–81]. These can be designed to deflect the shear layer over the sunroof so that the coherent vortex developed over the opening does not impinge on the trailing edge. Solid deflectors and dividing bars can be used[82;83]. Alternatively, the main coherent vortex can be broken into several small weak vortices using notched or mesh deflectors[84]. A comparison showing the differences in flow structures between a mesh deflector and no deflector are shown in Figure 7.

Suppressing rear window boom is more challenging, since it is difficult or undesirable to adopt a deflector solution in front of side window openings[85;86]. A reduction in boom has been demonstrated by increasing the size of the A-pillar vortex or by modifying the wake of the door side mirrors[87], however such modifications are likely to increase the overall levels of wind noise with the side windows closed. Increased levels of turbulence, as would be found on-road, can also reduce the level of side window boom through the break-up of larger scale coherent structures by the oncoming flow unsteadiness[88]. One solution is to de-tune the cavity by opening another window on the vehicle.

Door Gaps. Gaps between body panels are also a cause of cavity noise. In addition to isolating noise due to leakage, body gaps are taped over during aeroacoustic wind tunnel testing to avoid any gap noise, since body panel gap variation between individual vehicles can confuse the measurement of other acoustic sources. The underlying mechanism is related to that of a Helmholtz resonator, with pressure fluctuations from the turbulent boundary layer large enough to excite the fluid within the cavity leading to noise generation[76].

Unsteady Environment

The wind conditions experienced on-road differ significantly from those typically experienced during vehicle development. Both the computational fluid dynamics (CFD) and wind tunnel environments typically subject a vehicle to steady-flow conditions and therefore there can be concern that data obtained under steady flow may not fully capture how the interior noise of a vehicle responds to fluctuations in the inherently unsteady external surroundings.

The various sources of oncoming flow unsteadiness and their effects have been investigated by many researchers including[60;89–94] and are summarised by Sims-Williams[95]. As a vehicle travels along the road it experiences gusts in the natural wind; unsteadiness created by driving behind a vehicle; and by traversing through the steady wakes of roadside objects. The combination of each of these factors can lead to time-varying changes in flow speed and yaw angle over the vehicle. Since the aeroacoustic sources as shown in Figure 4 have a strong sensitivity to changes in flow speed and yaw angle, this can strongly affect the noise heard inside the cabin[96].

This has led to a number of studies taking place comparing the wind noise measured under unsteady conditions to that measured under steady conditions. These can be grouped into those that assess the vehicle response when applying oncoming flow unsteadiness, and those that use quasi-steady approaches.

Simulation of Transient Onset Conditions

To take advantage of the controlled and more repeatable conditions experienced in the wind tunnel compared to on-road, a number of approaches is to simulate the effects of the unsteady onset flow through the use of turbulence generation systems. These include passive means, where turbulence can be generated for example by positioning vehicles in the nozzle of an aeroacoustic wind tunnel[97;98]. Passive methods suffer from not being able to generate the longer turbulence length scales as would be experienced on-road[99]. Alternatively, active methods using aerofoils or vanes positioned upstream of the test section to generate varying levels of turbulence can be used[100–102], allowing a number of transient aeroacoustic studies to take place, including[103–105].

CFD provides more freedom to include transient inlet conditions without being limited by the hardware required to generate them. However, the subsequent simulation times often need to be longer to capture the required unsteady scales[106;107].

Quasi-Steady Simulation

A vehicle can be said to have a quasi-steady response if the vehicle responds in the manner it would under steady

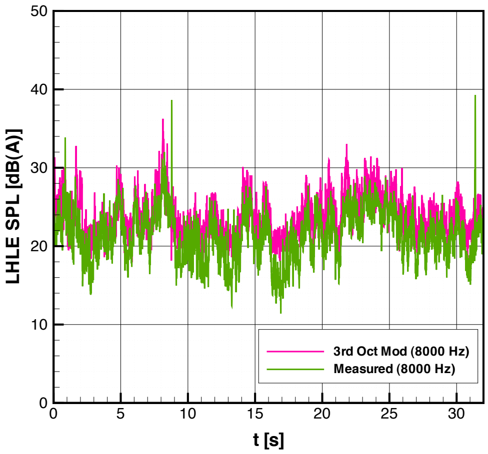

Figure 8. Comparison of simulated and measured cabin noise using a modulation approach[96;109]

conditions. When simulating unsteady wind noise, these approaches typically involve stitching together the vehicle cabin noise response from a series of discrete steady-state wind conditions to simulate how a vehicle would sound when the flow conditions are fluctuating.

One approach[108] is to assess how the level cabin noise increases using the power relationship between flow speed and sound pressure level, as described previously, under steady conditions. In addition to this, time histories of flow speed data can be collected on-road under a range of conditions. These can then be combined to develop corresponding time histories of cabin sound pressure level.

A similar approach[96;109] can be used by first recording the vehicle cabin noise under a specific flow speed and yaw angle. The characteristic change in sound pressure level is also measured for a range of different flow speeds and yaw angles under steady conditions in the wind tunnel. This characteristic can then be combined with time histories of flow speed and yaw angle measured on-road to develop a corresponding time history of how the sound pressure level changes when experiencing these different flow conditions. Finally, this can be used to modulate the amplitude of the original recording, to provide a simulation of what that vehicle would sound like under those wind conditions. Figure 8 shows an example of the resulting simulated noise compared with the equivalent measured on-road data, showing the similarity between the two signals. The work concludes that the quasi-steady approach is valid for wind noise fluctuations up to 2–5 Hz, beyond which there is both less energy in the fluctuations and the human ear becomes less sensitive in hearing the resulting modulation.

Instead of modulating a continuous recording, a series of individual recording can be made in the wind tunnel at discrete flow speeds and yaw angles. These can then be blended together based on measured on-road time histories of flow speed and yaw angle[110].

Impact of Unsteady Onset Flow on Aeroacoustics

An advantage of the different approaches described above, compared with simply assessing vehicles by driving them subjected to natural wind, is that it allows different vehicles to be assessed under the same wind conditions. Or alternatively, it is possible to assess cabin noise for a given vehicle as subjected to a range of different wind conditions without directly having to experience them.

Unsteady onset flow will result in a different time-averaged cabin noise to zero yaw wind tunnel conditions, and may result in a difference to that which would be predicted by a quasi-steady approach. However, the greatest importance of the unsteady onset flow is likely to be linked to the modulation that it introduces to the cabin noise. This requires consideration of the unsteady on-road environment, vehicle (form) noise as a function of yaw angle and psychoacoustic perception of noise. Jury testing of simulated cabin noise modulated by on-road wind conditions[21] has shown the importance of noise modulation compared with baseline noise level in terms of passenger perception, finding that an increase in wind noise yaw sensitivity of a vehicle by approximately 0.1 dB/degree was equivalent to an increase in 1 dB of noise at zero yaw in the wind tunnel.

Conclusions

Vehicle aeroacoustic performance has a strong influence on customer perception and also has importance for safety and comfort.

Automotive wind noise sources span several orders of magnitude in both frequency and level, with acoustic sources not combining linearly in terms of sound pressure level or perception. This results in diverse implications. A broadband source with significant sound pressure level in isolation may be effectively masked by a slightly louder source. On the other hand, a narrowband source (tone) with a negligible contribution to SPL could cause very significant annoyance to a customer. The consideration of separate spectral contributions and the use of psychoacoustic parameters are important to be able to assess aeroacoustic performance. A key point is that the human brain is not only sensitive towards the level steady broadband noise, but distinctive features such as tonality or modulation draw the attention of the vehicle occupant and impact negatively on perception.

Wind noise performance was once linked mainly to the quality of sealing and hence level of monopole noise inside the passenger compartment. However, for a modern vehicle, effective sealing should be considered to be a basic requirement. This is not to say that achieving robust sealing is easy, including because sealing is influenced by build quality, component ageing and by aerodynamic loading on doors when driving at speed.

Given effective sealing, cabin noise depends on the strength of noise sources on the vehicle exterior and their ability to transmit to the vehicle interior. Glazed surfaces are of particular importance as the opportunities for introducing attenuating material are more limited than for areas of bodywork. Attenuation in the noise pathway from sources on the exterior to the vehicle interior will continue to play an important role in controlling cabin noise, with a particular emphasis in achieving attenuation efficiently in terms of component mass.

Minimising aeroacoustic noise sources by engineering of the vehicle form provides an opportunity to improve wind noise performance without the increased component mass and cost associated with increasing attenuation in the noise transmission path. Hence this has become an important element in the development of modern vehicles.

Vehicles on the road are subject to unsteady onset flow conditions, in particular with varying yaw angle. Form noise must obviously be considered across a representative range of yaw angles. Further, the modulation of cabin noise due to time-varying onset flow conditions can have a significant impact on passenger perception. A key to achieving future vehicle refinement is bringing together an understanding of unsteady onset flow conditions, their impact on cabin sound pressure level and modulation and in turn the impact of noise level and modulation on psychoacoustic perception.

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