

Evaluation of the Aerodynamic and Aeroacoustic Response of a Vehicle to Transient Flow Conditions

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ABSTRACT

A vehicle on the road encounters an unsteady flow due to turbulence in the natural wind, unsteady wakes of other vehicles and as a result of traversing through the stationary wakes of roadside obstacles. Unsteady effects occurring in the sideglass region of a vehicle are particularly relevant to wind noise. This is a region close to the driver and dominated by separated flow structures from the A-pillar and door mirrors, which are sensitive to unsteadiness in the onset flow. Since the sideglass region is of particular aeroacoustic importance, the paper seeks to determine what impact these unsteady effects have on the sources of aeroacoustic noise as measured inside the passenger compartment, in addition to the flow structures in this region. Data presented were obtained during on-road measurement campaigns using two instrumented vehicles, as well as from aeroacoustic wind tunnel tests.

Conventional admittance functions relating oncoming flow yaw angle to cabin noise response are generally not suitable due to the non-linear steady state characteristics obtained in the wind tunnel, i.e. the cabin noise does not vary with yaw angle in a linear fashion under steady-state conditions. Therefore two alternative approaches were used based on instantaneous conditions to determine a quasi-steady predicted cabin noise time-history. These techniques demonstrated that the cabin noise response to oncoming flow unsteadiness remained generally quasi-steady up to fluctuation frequencies of approximately 2 to 5 Hz, where above this smaller flow scales have a progressively smaller impact on cabin noise fluctuations. Therefore, with a measurement of both the cabin noise in the steady environment of the wind tunnel and the unsteady onset flow conditions, the fluctuations (and thus the modulation) of the wind noise under these unsteady conditions is able to be predicted.

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INTRODUCTION

A vehicle on the road encounters an unsteady flow due to turbulence in the natural wind, unsteady wakes of other vehicles and as a result of traversing through the stationary wakes of roadside obstacles. These various sources of oncoming flow unsteadiness and their effects have been investigated by various researchers including [1, 2, 3, 4, 5, 6] and are summarised by Sims-Williams (2011) [7]. Previous work on unsteady on-road effects on aeroacoustics has been published by [8, 9, 10, 11, 12].

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structures from the A-pillar and door mirrors, which are particularly sensitive to unsteadiness in the onset flow.

Previously, work by Oettle et al. (2012) [10] showed that deviations in the sideglass surface pressure distribution from that predicted under steady-state condition can occur, isolated particularly to the region nearest the A-pillar under leeward flow conditions. This work extends that investigation, determining the transient sideglass surface pressure response for an alternative vehicle geometry, seeking to determine what impact these unsteady effects have on the aeroacoustic noise inside the passenger compartment as well as on the vehicle exterior.

EXPERIMENTAL METHOD

Two vehicles were used during the course of experimentation, recording data relating to cabin noise and sideglass surface pressures respectively. In addition to either the surface pressures or cabin noise, a roof-mounted probe was incorporated to record the instantaneous oncoming flow conditions.

Test Vehicles

A vehicle typical of a European luxury saloon was used as the test vehicle, shown in [Figure 1](#) and was the same model as used in the previous research of Oettle (2013) [13] incorporating Oettle et al. (2012, 2011, 2010) [10,11,12]. As shown, a probe was mounted on the roof of the vehicle for the measurement of instantaneous flow conditions. The coordinate system that is used throughout the paper is shown in [Figure 1](#) and [Figure 2](#).

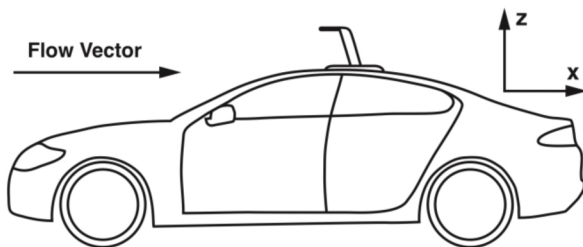


Figure 1. Test vehicle showing location of probe

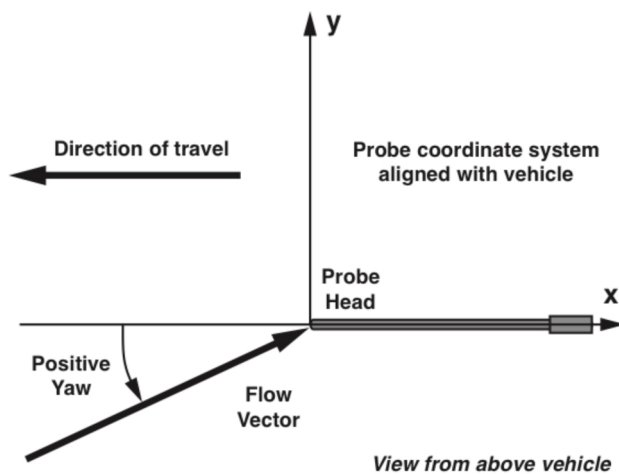


Figure 2. Plan view: Probe and vehicle coordinate system

Surface pressure investigations were also performed the European two box hatchback vehicle described by Lawson et al. (2007) [14]. The same roof-mounted probe as corresponding coordinate system was used as with the cabin noise measurements.

On-Road Data Collection

Roof Mounted Probe

To measure the flow over both vehicles, a roof-mounted 5-hole probe was used, as in Oettle (2013) [13]. The probe tip was positioned approximately 320 mm above the vehicle's roofline, and approximately 70 mm in front of the B-pillar, as shown in [Figure 1](#). The probe was manufactured and calibrated in isolation using facilities at Durham University. Five SensorTechnics HCLA12X5DB pressure transducers were used to measure the probe pressures. These measure differential pressure and have a range of ± 12.5 mbar. The transducers were packaged into a single enclosure with a common reference and located within the probe mounting. The reference port was connected via a PVC tube to a location in the trunk of the vehicle. The probe mounting was attached to the roof of the vehicle magnetically.

A probe and tubing transfer function correction was applied, for magnitude and phase, to all on-road data for both the roof mounted five-hole probe and the sideglass pressure tapplings. This is described by Irwin et al. (1979) [15] and implemented for probe measurements here as described by Sims-Williams and Dominy (1998) [16]. With the probe and remote transducers used in the investigation, this approach allows a frequency response in excess of 500 Hz. This significantly exceeds the required response for this application as higher frequency fluctuations contained in the wind are also correspondingly small in physical size and are therefore not correlated over the scale of the vehicle.

Any probe installation location will be a compromise between measuring the incoming flow that the vehicles sees, minimizing the influence of the probe on the flow around the vehicle, and minimizing the influence of the vehicle on the flow at the probe.

It was important for the design of the probe mounting not to have a significant impact on the flow at the probe tip or to affect flow around the vehicle in either the sideglass region or in other areas that may affect the noise heard inside the cabin. In addition, it was important that the probe had a minor impact on aeroacoustic measurements.

The approach used here (e.g. positioning the probe some distance off the vehicle and using a probe calibration performed in isolation rather than in situ) means that the yaw angles and other quantities reported are the actual values at the probe location and this is known with certainty. Steady state wind tunnel measurements show that the probe experiences a speed up of both longitudinal and lateral velocity components. This has been shown to be a good probe location for accurate measurement of yaw [13], although the yaw angle seen by the probe still becomes slightly exaggerated at higher yaw angles. While it may be tempting to "correct" for these effects that would assume that the flow around the vehicle in a transient condition matches that in the steady state condition. This investigation concerns the comparison between the aerodynamic response of the

vehicle under steady state and transient conditions and so such an assumption would not be appropriate a priori.

Sideglass Pressures

Surface pressures were measured on the front sideglass using both surface-mounted “lollipop” taps on the standard glass sideglass as described by [14], and using a drilled Perspex sideglass moulded to the shape of the production glass with 1.24 mm OD hypodermic stainless steel tubing bonded in position. Pressures were measured using separate SensorTechnics HCLA12X5DB pressure transducers located inside the cabin connected to each surface taping via PVC tubing. As for the probe measurement, pressures were measured relative to trunk pressure. Pressure coefficient C_p was defined based on the static and dynamic pressure measured by the 5-hole probe. Again this provides something that is known with certainty in the on-road case as well as in the wind tunnel.

$$C_p = \frac{P_{\text{Tap}} - P_{\text{Probe Static}}}{\frac{1}{2}\rho U_{\text{Probe Resultant}}^2}$$

Data Acquisition

To log the output from the pressure transducers, a National Instruments NIDAQmx USB-6218 data logger was used. This was controlled by a laptop running control software developed in-house. Data were also received from a GPS device that was simultaneously logged with the pressure transducer data from the data logger using the same control software. The GPS data included details of the velocity and heading of the vehicle, in addition to information on the location of the vehicle and time of the experiment. The pressure transducer data were logged in sets of 16384 points at 500 Hz, therefore giving a logging duration of 32.768 s. This logging time was considered suitable to capture the transient nature of the on-road environment. To avoid aliasing, the signal from each of the pressure transducers was passed through a 250 Hz second-order low-pass filter.

Cabin Noise Measurement

A Head Acoustics Aachen head with torso was used to record the cabin noise. This was positioned on the front left (passenger) seat of the vehicle and fixed securely to prevent any additional noise generation. The ventilation system was switched off during testing.

The acoustic head was connected to the logging computer via a Head Acoustics front-end and controlled through the Head Acoustics HEAD Recorder software. Logging took place at 44.1 kHz. In addition to the combined trigger for both flow and audio logging systems, a 2 kHz tone was generated and silenced at the point of logging to assist synchronising the logging systems with a simultaneous video recording.

Head Acoustics ArtemiS software was used to extract SPL (sound pressure level) from the audio data collected both on-road and in the wind tunnel.

Wind Tunnel

The Pininfarina wind tunnel was used to assess the cabin noise response of the vehicle to discrete steady-state flow conditions. Instrumentation remained the same as for on-road data collection. The results reported here were obtained using a stationary ground boundary condition and static wheels. The results reported here were obtained using a stationary ground and wheels and without the Pininfarina turbulence generation system. Measurements were made at a range of turntable yaw angles from -20 degrees to $+20$ degrees at 2.5 degree increments. The nominal wind tunnel velocity matched the on-road driving velocity. As discussed above, the yaw angles reported in the results correspond to those measured at the probe since this is what is always known with certainty.

The steady-state surface pressure coefficient versus yaw characteristics were obtained via wind tunnel measurements and by conditional averaging of on-road measurements. While differences could be observed between these two approaches in some cases from the point of view of time-averaged C_p , both methodologies for determining the steady-state characteristics yielded the same conclusions in terms of the vehicle's transient response.

RESULTS AND DISCUSSION

Typical Admittance and Transfer Function Approaches

The aerodynamic admittance is a common method used to quantify the aerodynamic response of a vehicle to unsteadiness. This is usually defined for aerodynamic coefficients, but there is no reason why may not be defined in terms of aeroacoustic admittance, as in the following equation:

$$\chi(f)^2 = \frac{G_{LL}(f)}{\left(\frac{dL}{d\psi}\right)^2 G_{\psi\psi}(f)}$$

This is similar to a transfer function defined as the ratio between the SPL and yaw angle spectra. As f tends to zero, it would be expected that the admittance would tend to unity, with the transfer function tending to the sensitivity of changes in SPL to yaw angle measured under the steady conditions of the wind tunnel. Both approaches are shown in general terms by [Figure 3](#) where the oncoming flow conditions are described by $F(t)$ and the vehicle response by $R(t)$.

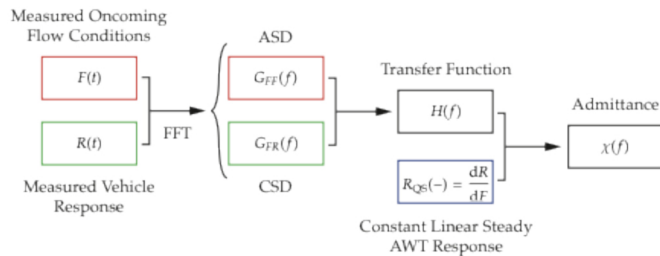


Figure 3. Method to determine the transient response of a vehicle via admittance

When considering aerodynamic admittance, for example based on a side force or yaw moment coefficient on a vehicle, the coefficients tend to vary linearly with yaw angle. Therefore, the rate of change (gradient) between the force coefficients and yaw remains independent of the particular instantaneous oncoming yaw angle.

However, when considering localised surface pressure changes, for instance the pressure at a particular point on the sideglass, see Oettle et al. (2012) [10], the behaviour may not be linear, for instance on the sideglass region adjacent to the A-pillar. This is also particularly the case when considering the response of cabin noise to yaw angle, where it is clear that owing to the greater amount of flow separation at the extremes of yaw angle, that the cabin noise at both positive and negative yaw angles is greater than at a zero yaw condition. Therefore the cabin noise is not at all linear with yaw angle and therefore an equivalent aeroacoustic admittance approach would not be appropriate. Indeed, when determining the aeroacoustic admittance on-road, this term would vary depending on the range of yaw angles experienced.

Cabin noise is not only affected by variations in oncoming yaw angle, but also to fluctuations in flow speed. Typically the relationship between oncoming flow speed and cabin noise scales with oncoming flow speed raised to the power of the order of 6, indicating dipole dominated aeroacoustic sources. Therefore, instead of a single input - single output system, a multiple input - single output system must be considered, discussed in further detail by Bendat and Piersol (1993) [17]. This does not preclude such a transfer function assessment *per se*, it is the non-linear response of cabin noise to yaw angle which provides the challenge, as it could be imagined that the logarithmic response of the cabin noise to flow speed could be successfully linearized.

Therefore an alternative approach was sought to be able to assess the response of the vehicle to fluctuations in the oncoming flow when the steady-state response is non-linear.

An Alternative Linearized Transfer Function Approach

To assess the nature of the vehicle cabin noise response, a simulation technique was implemented which used the cabin noise response to both oncoming yaw and flow speed

measured in the wind tunnel, combined with the measured transient flow characteristics measured by the probe on the vehicle roof on-road to predict the instantaneous sideglass pressure. This directly compares the behavior of the vehicle on-road to that predicted by the wind tunnel. Therefore any non-linearities in the wind tunnel steady-state characteristics are removed and converted into a continuous predicted time-history of cabin noise. In the case of localized sideglass surface pressure tapings, this technique was previously introduced by Oettle (2012) [10]. Figure 4 outlines a generalized form of this process.

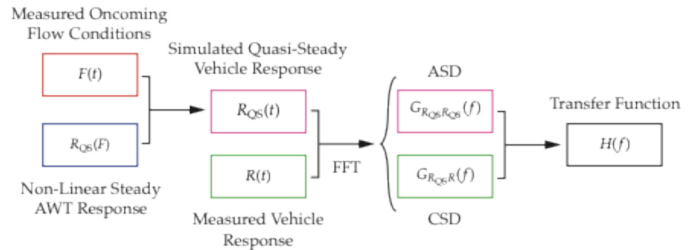


Figure 4. Method to determine the transient response of a vehicle via a linearized approach

This process results in a transfer function whereby a value of unity implies that the vehicle response to oncoming flow fluctuations is equal to that predicted in the steady environment of the AWT i.e. the response is quasi-steady. A transfer function of greater than unity implies that the vehicle responds to a greater extent than predicted by the instantaneous oncoming flow conditions alone, whilst a response of less than unity implies a response less than predicted under steady conditions.

It has been shown, for instance by Schröck (2009) [18] that for the aerodynamic response of a vehicle, a transfer function of unity would be expected at lower frequencies for scales much greater than the vehicle, where the response can be considered to be quasi-steady. At higher frequencies, the vehicle response is no longer quasi-steady, although the higher-frequency, small-scale fluctuations much smaller than the size of the vehicle have a progressively decreasing impact of the vehicle response, leading to a transfer function of less than unity. In the intermediate frequency range, scales of unsteadiness may exist that are sufficiently large and of sufficient energy to influence a vehicle, but not so large that they can be considered to be quasi-steady. This is discussed further in Sims-Williams [7]. These effects can lead to transfer function values of greater than unity and these are sometimes associated with resonances of the vehicle suspension system in the case of vehicle forces.

The alternative linearized approach simplifies the analysis of the system, since multiple-input problems can be simplified to consider only a single input, avoiding the need for a multiple input - single output analysis. For instance, it has been shown that the noise inside the cabin of a vehicle is influenced by both the oncoming flow speed and yaw angle. Instead of assessing these as independent inputs to the

system, these inputs are linearized to produce a single input of the expected cabin noise as determined under the steady conditions of the wind tunnel. This single input is then assessed against the single output of the measured cabin noise to determine the response of the system.

Steady-State Characteristics

The steady-state wind tunnel obtained overall cabin noise SPL response characteristic is shown in *Figure 5*. This presents the overall cabin noise measured at the left-head, left-ear position at a series of yaw angles and flow speeds in the wind tunnel.

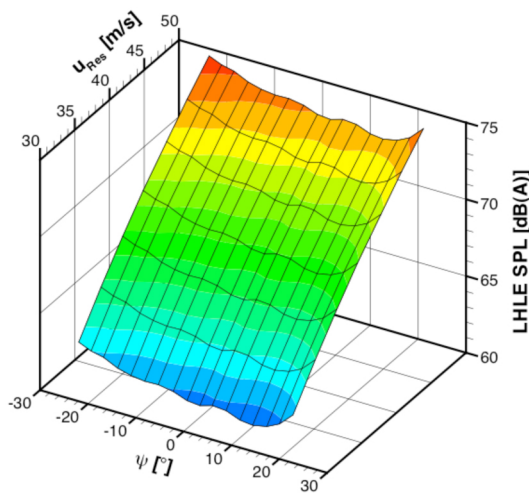


Figure 5. AWT cabin noise characteristic

This is a compound surface of the yaw and flow speed cabin noise characteristics determined in the AWT. In producing the surface, multiple yaw sweeps and a zero-yaw speed sweep were combined to produce an overall surface, with interpolation used for the behaviour between the measured conditions. In addition to the overall level, characteristics of the various third-octave frequency bands of cabin noise were also produced using the same AWT data.

For surface pressures only a pressure coefficient versus yaw characteristic is required. These were obtained from wind tunnel measurements and by conditional averaging of on-road measurements and both approaches yielded the same conclusions in terms of the vehicle's transient response.

For the case of the sideglass pressure tapping data, instead of determining the steady-state response in the wind tunnel, the time-averaged response was used. This method used a 2.5° spaced Bin Average process to take each and every 4 seconds period of the on-road 5-hole probe sampled data from a collection of 252 × 32s data. The time-averaged pressure coefficient was then evaluated for each sideglass tapping per bin, with the central bin located at $\pm 1.25^\circ$, and the average flow yaw angle for each sample used as the actual bin yaw angle (i.e. the independent variable for subsequent simulation).

The resultant output file from this process was a time-averaged pressure coefficient against averaged flow yaw angle at 2.5° intervals for each sideglass tapping, between $\pm 22^\circ$. An example of the output of this method can be seen in *Figure 6* for 3 sideglass tappings.

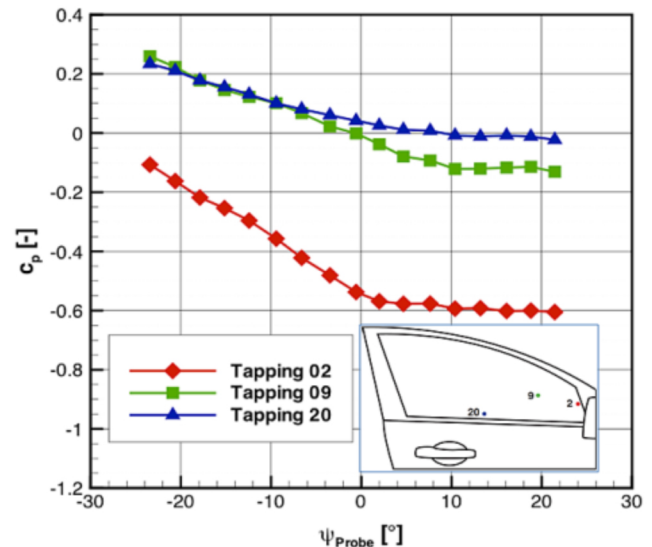


Figure 6. Pressure Coefficient against Flow Yaw Angle (Bin Averaged)

Experimental Prediction and Transfer Functions

To create the overall transfer function comparing both the measured and quasi-steady predicted sideglass pressure fluctuation, the time-averaged sideglass pressure tapping characteristics were first combined with the probe measured oncoming flow conditions for each of the sets of on-road data collected. This results in a quasi-steady simulated time-history that can be compared with the equivalent on-road measured pressure tapping fluctuations. A comparison between these two signals is shown in *Figure 7* reproduced from Oettle et al. (2012) [10], showing a visually good agreement between the transient on-road data and the wind tunnel quasi-steady predicted result.

The first observation is that the agreement is very good, with the behaviour at the scales that are visible on a 30s time trace being closely quasi-steady. It is, of course, difficult to assess frequencies much higher than 1 Hz in this way and so further analysis is required to assess the vehicle response at higher frequencies. It is possible to calculate a transfer function between the predicted and measured traces and this provides some insight, but the transfer function becomes corrupted by any self-excited effects. This was discussed and demonstrated in Oettle et al. (2012) [10]. A better approach is to compare the measured level of unsteadiness over a short duration (e.g.: 4s) with the corresponding predicted level of unsteadiness (which is a prediction of surface pressure unsteadiness due only to unsteadiness in the oncoming flow).