

Assessing the Aeroacoustic Response of a Vehicle to Transient Flow Conditions from the Perspective of a Vehicle Occupant

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ABSTRACT

On-road, a vehicle experiences unsteady flow conditions due to turbulence in the natural wind, moving through the unsteady wakes of other road vehicles and travelling through the stationary wakes generated by roadside obstacles. Separated flow structures in the sideglass region of a vehicle are particularly sensitive to unsteadiness in the onset flow. These regions are also areas where strong aeroacoustic effects can exist, in a region close to the passengers of a vehicle. The resulting aeroacoustic response to unsteadiness can lead to fluctuations and modulation at frequencies that a passenger is particularly sensitive towards. Results presented by this paper combine on-road measurement campaigns using instrumented vehicles in a range of different wind environments and aeroacoustic wind tunnel tests.

A new cabin noise simulation technique was developed to predict the time-varying wind noise in a vehicle using the cabin noise measured in the steady environment of the wind tunnel, and a record of the unsteady onset conditions on the road, considering each third-octave band individually. The simulated cabin noise predicted using this quasi-steady technique was compared against direct on-road cabin noise measurements recorded under the same flow conditions to assess the response of the vehicle to oncoming flow unsteadiness.

The technique predicted the modulation of the wind noise under unsteady on-road conditions with good fidelity. This is because the cabin noise response to oncoming flow unsteadiness remained generally quasi-steady up to fluctuation frequencies of approximately 2 to 5 Hz, with fluctuations at higher scales having a progressively smaller impact, and because most of the onset flow fluctuation energy on the road occurs at frequencies below this threshold.

The relative impact of the baseline level of cabin noise and the sensitivity of the cabin noise to changes in yaw angle were assessed in terms of occupant perception and this highlighted the importance of modulation. This can provide guidance when assessing the on-road wind noise performance of vehicle geometry modifications and of different vehicles.

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INTRODUCTION

On-road, a vehicle experiences unsteady flow conditions due to turbulence in the natural wind, moving through the unsteady wakes of other road vehicles and travelling through the stationary wakes generated by 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 [7]. Previous work on unsteady on-road effects on aeroacoustics has been published by [8, 9, 10, 11, 12, 13]. Separated flow structures in the sideglass region of a vehicle are particularly sensitive to unsteadiness in the onset flow. These regions are also areas

where strong aeroacoustic effects can exist, in a region close to the passengers of a vehicle. The resulting aeroacoustic response to unsteadiness can lead to fluctuations and modulation at frequencies that a passenger is particularly sensitive towards.

Previous research [11] investigated the surface pressure response of the front sideglass region to oncoming flow unsteadiness. This found that, with the exception of the region closest to the A-pillar, the pressures behaved in a quasi-steady manner up to 2-10 Hz. Beyond this, higher frequency unsteady fluctuations had a progressively reduced impact on the

sideglass pressures. Therefore, with knowledge of the surface pressure profiles measured under a range of steady conditions (for instance, in the wind tunnel), using the instantaneous oncoming flow yaw angle measured on-road, the surface pressure profile could be predicted.

Deviations to the quasi-steady response in the sideglass surface pressure distribution from that predicted under steady-state conditions were found to occur, isolated particularly to the region nearest the A-pillar under leeward flow conditions.

This work was developed [10] to investigate what impact these unsteady effects have on the aeroacoustic noise inside the passenger compartment. Using a quasi-steady cabin noise simulation technique, based on modulating the overall level of cabin noise as recorded under the steady conditions of the aeroacoustic wind tunnel, evidence of a quasi-steady cabin noise response up to 2-5 Hz was found to occur.

This work extends that investigation, using a refined cabin noise simulation technique to determine what impact unsteady effects (particularly the non-quasi-steady surface pressure behaviour in the A-pillar region) have on the aeroacoustic noise inside the passenger compartment.

In addition, one key advantage of the simulation technique is that it allows unsteady cabin noise to be produced, listened to and subjectively assessed through jury testing. Using this, the relative impact of cabin noise modulation as perceived by a vehicle occupant due to unsteady oncoming flow conditions is also assessed.

EXPERIMENTAL DATA COLLECTION METHODS

The experimental data collected were used for two purposes. Firstly, to generate the simulated aeroacoustic cabin noise, data were recorded under the steady flow conditions of the AWT to capture the steady-state response of the vehicle. Unsteady oncoming flow conditions under a range of conditions were also measured on-road. Using the method described later in the paper, these two sets of data were combined to generate the unsteady aeroacoustic cabin noise simulation as would be heard on-road under the measured flow conditions.

In addition, the cabin noise was also recorded on-road under the same unsteady flow conditions, and these data were used to compare with the predicted cabin noise to compare and validate the simulation.

The following sections outline the instrumentation and measurement techniques used to collect the data required for both the cabin noise simulation and its validation.

Test Vehicle

A vehicle typical of a European luxury sedan (saloon) was used as the test vehicle, shown in Figure 1 and was the same model as used in the previous research of [14] incorporating [10,11,12,13]. As shown, a probe was mounted on the roof of the vehicle for the measurement of instantaneous flow conditions.

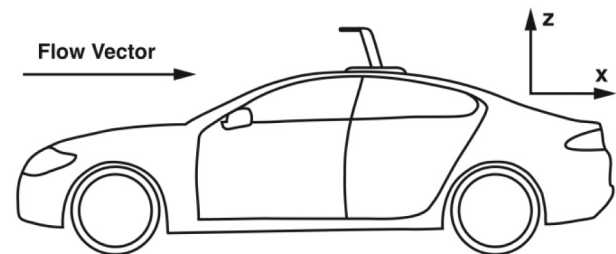


Figure 1. Test vehicle showing location of probe

Roof-Mounted Probe

To measure the oncoming on-road wind environment as experienced by the vehicle, a roof-mounted 5-hole probe was used, as in [14]. 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 boot 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 tapings. This is described by [15] and implemented for probe measurements here as described by [16]. With the probe and remote transducers used in the investigation, this approach allows a frequency response in excess of 500 Hz, significantly exceeding the required response for this application.

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, 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 [14], although the yaw angle seen by the probe still becomes slightly exaggerated at higher yaw angles. While it may be tempting to “correct” for the effect of the flow around the vehicle on the probe measurement, 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*.

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 32.8 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 low-pass filter.

Cabin Noise Measurement

A Head Acoustics binaural 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 and the vehicle ventilation system was switched off during testing. The acoustic head was connected to the logging computer via a Head Acoustics frontend 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 and wheels and without the Pininfarina turbulence generation system in operation. 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. For the wind tunnel measurements as well as the on road measurements the yaw angles reported in the results correspond to those measured at the probe since this is what is always known with certainty, as discussed above.

UNSTEADY WIND NOISE SIMULATION METHOD

An unsteady wind noise simulation technique was implemented that used the vehicle cabin noise measured under the steady-state conditions of the aeroacoustic wind tunnel combined with unsteady flow condition data measured by a vehicle travelling on-road. The technique built upon those introduced in [10, 11], whereby a quasi-steady approach was used to assess the surface pressure response on a vehicle front sideglass and the level of aeroacoustic broadband cabin noise fluctuations respectively.

Broadband Modulation Approach

The broadband cabin noise approach of [10] is described using the four following steps:

Measurement of On-Road Flow Conditions

Using the flow-measurement probe mounted on the roof of the vehicle, the instantaneous oncoming flow unsteadiness was measured under a range of wind and traffic conditions whilst travelling on highways at constant vehicle speed.

The range of oncoming flow speeds and yaw angles as measured throughout the test campaign using the roof-mounted probe are presented by Figure 2 and Figure 3 respectively, plotted with a normal distribution.

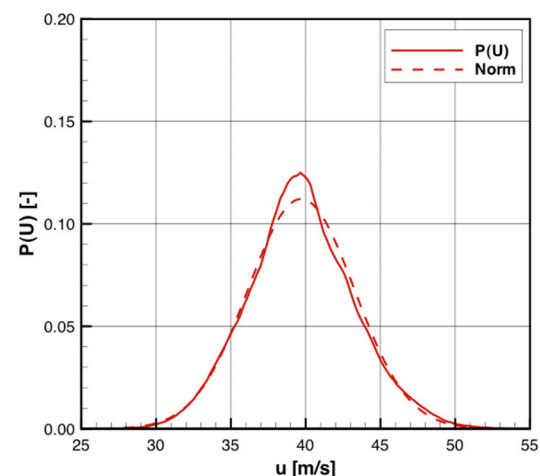


Figure 2. Probability distribution of on-road resultant flow speed

The resultant flow speed distribution of Figure 2 closely follows a normal distribution, indicating that the resultant flow speed data was reasonably representative of what would be experienced under normal driving conditions, with no bias towards high or low wind conditions. In the case of the yaw angle distribution of Figure 3, the bias towards zero yaw