TURBULENCE EFFECTS ON AERODYNAMIC NOISE OF ROAD VEHICLES

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INTRODUCTION

Design for vehicle interior sound quality forms a large part of motor car development. Customers not only expect state-of-the-art technology, efficient engines, ride comfort and attractive design, but the perception of overall product quality is of utmost importance. Vehicle interior cabin noise thus plays an important role, as cars should not only be visually attractive, but should also be quiet and have a high acoustic quality. This primarily means a reduction of structure-born noise, such as vibration from the engine mounts, gear train or the interaction between tyres and the road surface. Recently however, wind noise has also become a concern for car manufacturers. Mechanical noises of cars have been subject to intensive research and, as a result, are now low [1]. At high driving speeds (eg. >100 km/hr), the relative wind experienced by the moving vehicle creates interior cabin noise, which can dominate the other noise sources. This relative wind is the vector sum of the road velocity and the atmospheric wind. Vehicle manufacturers are most interested in noise characteristics under yawed conditions. For such conditions, there must always be a cross wind component from the atmospheric wind, fig. 1. Since the atmospheric wind is turbulent, the relative wind is turbulent, leading to intermittent gustiness and hence annoying wind noise.

Turbulence and Aerodynamic Noise

Aerodynamic noise inside vehicles originates mainly from unsteady pressure fluctuations on the vehicle exterior surfaces, causing fluid/structure interaction. These pressure fluctuations mostly stem from turbulent boundary layers, turbulent flow separations and natural turbulence inherent in the oncoming air flow. Other noise sources are vortex shedding from antennae, side mirrors or other protrusions, as well as aspiration or leakage noise through the door and window seals [1]. Theoretical research into aerodynamic and turbulence noise has its origins in the studies of Lighthill [2], which have been further developed more recently by Howe [3] and others.

Over the past two decades or so, practical wind noise research has been conducted by car manufacturers and research organisations world wide. It is now one of the largest users of wind-tunnel time. Major improvements in reducing cabin noise due to improvements in vehicle aerodynamics have been achieved. Typical wind noise source areas have been identified and car designs improved. Some of the major changes are; flush surfaces, particularly the transition from windscreen to side window, larger A-pillar radii and avoidance of flow separations by using smoother, more rounded shapes and surfaces [4].

Measuring Turbulence and Aerodynamic Noise

Because rubber sealing and sound absorbing materials used to dampen the interior noise are adding significantly to the cost of new production vehicles [5], ways of reducing the interior noises at their source are being investigated. Research development work to improve vehicle wind noise characteristics consists of on-road and wind-tunnel tests, usually with full-sized cars.

However all major vehicle wind tunnels are of the smooth flow type. Yet atmospheric winds exhibit turbulence intensities of up to 30%, and whilst driving at high speed, relative turbulence intensity can be up to 10%, with varying scales [6]. Extensive on-road tests have shown that the peak in the relative wind spectrum ranges from 0.1 to 10 Hz, with the average at about 1.0 Hz [6]. Turbulence may be measured by using constant temperature hot-wire anemometers (CTA). The wire sensors are very small, and can thus be fixed to the ouside of a vehicle without adding significant parasitic noise to the overall noise signature. Frequency resolution of CTA's is very high, with the major drawbacks being the involved calibration procedures, fragility of the probes and sensitivity to dirt accumulation and ambient temperature variations. Two other methods of measuring the time-varying flow field currently being investigated at *RMIT* are pressure tapping bumper bars of full-size vehicles [7], as well as using a pressure probe with a frequency response of up to 1.5 kHz, as described by Hooper [8].

Car interior noise is traditionally measured with single microphones placed in strategic positions inside the cabin. This is adequate for diagnostic work, such as noise ranking of vehicle modifications and their direct effect on the overall interior sound [5]. However, recording with binaural measurement equipment such as an artificial head is preferred, in order to replicate human hearing, which involves the left and right ear allowing pattern recognition, spatial hearing and selectivity. The dummy head is a mathematically defined simulation of the human head, shoulder and ear, with matching transfer functions and mechanical impedances. Thus with suitable recording and processing of the sound signal, human hearing equivalent judgement of different sounds becomes possible [9].

Questions arise as to the importance of simulating real on-road conditions such as fluctuating relative yaw angles and velocities. Do they need to be simulated in order to give accurate predictions from the wind-tunnel data for car interior noise? This could indicate whether or not vehicle aero-acoustic testing can be conducted in relatively quiet, smooth flow wind tunnels, with the time-varying noise being predicted from smooth flow measurements (ie a quasi-steady prediction), or if tunnels which simulate all, or part of the turbulent spectrum are needed. The quasi-steady flow assumption must thus be investigated, which is the objective of this research program.

CASE STUDY

Vehicle Interior Noise: On-Road vs. Wind Tunnel

Studies have been conducted whereby cars have been tested on-road and in the *RMIT/Monash University* large industrial wind-tunnel. This facility currently has a turbulence intensity level of approximately 1%, with turbulence reduction screens installed. Prior to this, the turbulence was about 3%-4%. At a speed of 110 km/hr, the wind tunnel background noise is 79 dB(A) overall sound pressure level, measured one metre out-of-flow from the free shear layer. In-flow measurements at the same speed have shown a maximum sound pressure level of 100 dB at 700 Hz, using an inflow-microphone with nose cone. So far, the tunnel's plenum chamber walls and ceiling have not been acoustically treated. However acoustic wedges are to be installed, in order to reduce reflected noise.

Various combinations of test situations and equipment have been considered; single microphone, artificial head recordings, various speeds and yaw angles, single- and cross wire turbulence measurements. Initially, a car was taken for on-road tests with a single 1/2" condenser microphone fitted to the headrest of the front passenger seat, close to the side window. This is the same position as the left ear of the front passenger. Single wire CTA measurements were obtained to investigate turbulence, not yet considering yaw angles. The wire was fixed ahead of the left A-pillar, measuring the oncoming flow. Stationary wind data was taken along the road side, to estimate prevailing wind direction and strength throughout the day. It was attempted to simulate mean relative wind conditions and yaw angles in the full-scale wind tunnel, comparing the car's interior noise with the on-road measurements. Significant differences in sound pressure levels were observed, with the interior noise for the wind-tunnel case being considerably lower. This is primarily attributable to the lower turbulence levels and the fact that tyre and engine noise are not present when testing in the tunnel.

Spectrum of Sound Pressure vs. Frequency

The averaged spectra for single microphone measurements are shown in fig. 2. On-road and wind-tunnel results are compared. In both cases, the sound was high pass filtered at 200 Hz, in an attempt to get rid of low frequency mechanical noise components. Although the spectra do not look very different, the recordings still sound substantially different. This is so because the intermittency of temporal and spatial variations of on-road noise cannot be fully documented by single microphone measurements and standard spectral processing techniques. The general procedure of averaging several spectra to get a single average spectrum is believed to be inadequate. It would for example be more useful to analyse the wind noise by using Short Time Fourier Transforms, showing the results as a spectrogram of sound pressure level versus time and discrete frequency, indicating the temporal and frequency variations of the noise. Alternatively, wavelet analysis is being considered. These signal processing methods can show the intermittent changes in amplitude and frequency due to the gustiness of the wind, as heard when driving on-road.

Artificial Head Recordings

Binaural measurements with an artificial head were also made, fig. 3. The dummy head is placed on the front passenger seat, thus placing its left ear close to the front side window. Notable differences in the noise signature can be seen when comparing the left and right ear signals. This significantly influences the human perception of sound. Such effects cannot be achieved by using only one microphone. Only binaural recordings will allow human hearing equivalent evaluation of different noises for their sound quality features. Loudness, sharpness and roughness are objective noise evaluation quantities which are supposed to be related to subjective judgements. Simple sound pressure level spectra and dB(A) weighting are inadequate for indicating why the noises are so different between on-road and wind tunnel. More work is being conducted in this area, by developing signal processing and analysis techniques in-house.

CONCLUSION

Measurements to date have shown that whilst spectral characteristics of aerodynamic noise in a wind tunnel as compared to the on-road case are not very different, substantial differences do become apparent when listening to the recordings and examining their temporal structure. It is therefore seen as necessary to analyse the recordings for their psychoacoustical properties, employing binaural recording and alternative signal processing techniques, in order to identify the time-varying, turbulent wind noise components, which are perceived as annoying by vehicle occupants. Further results are expected to be available soon for detailed interpretation and discussion.

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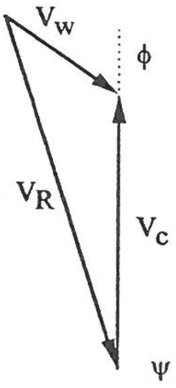
fig. 1:

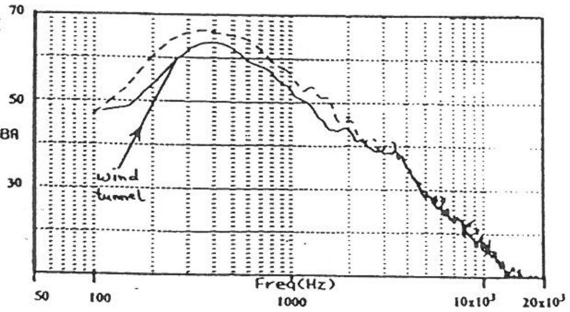


<u>symbols</u>: V_W = wind velocity relative to the road
V_R = relative wind as experienced by the car
V_c = car velocity relative to the road

ψ = yaw angle, as experienced by the moving vehicle
ϕ = wind angle, relative to the direction of travel (road)

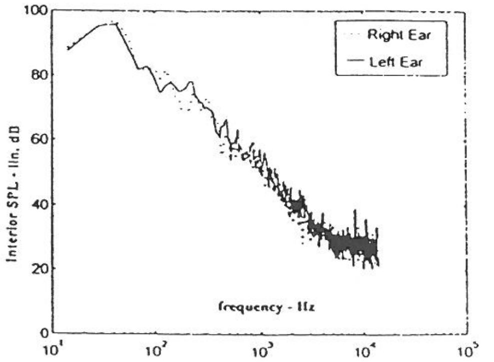
The relative wind velocity and yaw angle are the parameters simulated in the wind tunnel, by rotating the car on a turntable into the oncoming airflow.

fig. 2:



single microphone spectrum, on-road and wind tunnel compared.

fig. 3:



On-road noise recording at 100 km/hr, using a dummy head (shown below).