*Australian Wind Engineering Society, 4th National Workshop on Wind Engineering, 6-7 October '94; Sydney NSW, Australia.*

# Turbulence Effects on Aerodynamic Noise and its Relevance to Road Vehicle Interior Noise.

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***SUMMARY:*** This PhD thesis project was initiated in early February 1994 and aims to investigate the influence of air flow turbulence on aerodynamic noise, with particular reference to the interior noise of road vehicles. Vehicle aerodynamic noise is currently measured in wind tunnels with very low turbulence, whereas the on-road environment is turbulent. The mathematical analysis is in the area of aerodynamic noise and transient sound generation. The experimental work will comprise of model and full-scale wind-tunnel testing at the RMIT/Monash University Joint Facility, complemented by vehicle on-road tests.

***1. RATIONALE FOR PROGRAM:*** Wind noise inside automobiles has become an increasing concern for car manufacturers world wide, *George et al (1991)*. Mechanical noises such as the engine, transmission and rolling tyre noises have largely been reduced to a practical minimum on the modern motor car. At high driving speeds (eg. on freeways), these mechanical noises can be dominated by aerodynamic noise, originating from the external airflow over the vehicle body. This phenomenon constitutes a large proportion of complaints from car drivers to automobile manufacturers in Europe and the United States. Hence, investigation of automobile aerodynamic noise is one of the biggest users of wind-tunnel time world wide, second only to vehicle drag determination. BMW in Germany has recently commissioned a semi-anechoic wind tunnel with very smooth flow capabilities and acoustic testing facilities at a cost of approximately 30 million dollars (AUD). Other companies are following suit.

All the major wind tunnels currently used are of the smooth flow type, adopted from the aerospace research facilities, yet past research work has clearly shown that typical on-road conditions exhibit turbulence intensities of up to 10%, with varying scales. Hence concerns arise as to the validity of using smooth flow wind tunnels to predict on-road aerodynamic noise and the subsequent vehicle interior noise.

Also, this research work should not only be of benefit to the vehicle engineering field. Other areas are building and wind engineering, high-speed passenger train research and the aerospace engineering field, where knowledge and application of aerodynamic noise analysis forms an important part of project development and design.

***2. OBJECTIVES:*** The aim for this project is to investigate in what way turbulent flow will change the aerodynamic noise and hence the vehicle's interior noise characteristics. The findings will then address the question as to what on-road wind conditions, particularly turbulence, need to be simulated either in full or in part, in order to give accurate and reliable full-scale predictions from wind-tunnel data for car interior noise.

*3. PRIOR RESEARCH:* The literature review stage has been concentrated in two main areas of past research work, namely:

1. Analytical studies of aerodynamic noise generation, its mathematical and physical implications. (ie. quasi-steady versus turbulent flow)
2. The practical experimental issues involving aero-acoustic testing of vehicles in wind tunnels and on the road, including analysis of flow turbulence intensities and scales.

## 3.1 Theory:

The theoretical analysis of aerodynamic noise generation involves several areas of investigation. Numerous research papers are available, dealing with various aspects of aerodynamic noise, including turbulent flow noise components. The acoustic analogy and subsequent work by *Lighthill (1952,1954)* forms the base for most aerodynamic noise analysis. *Lighthill (1952)* grouped together all first order terms from the fluid dynamic equations of motion to the right hand side of the inhomogeneous wave equation as acoustic sources. This analogy is based on the fact that the sources of sound are represented by the difference between the more exact laws of fluid motion and the linear acoustical approximations, *Norton (1989)*. Hence the non-linearities, which represent stresses of the fluid, are the cause of the sound. *Blake (1986)* has followed up on this research and applied it to fundamental engineering problems and case studies, for example shear layer instabilities, flow tones and structural response to turbulent wall flow. *Howe (1993)* deals with a mathematical analysis on several aspects of turbulent and separated flow noise. *Norton (1989)* specifically referred to the significance of the unsteady Reynold's Stress component in Lighthill's Stress Tensor at low Mach number flows, and it's dominance as the right hand source term in the inhomogeneous wave equation (see Appendix). This will be an important parameter to be measured in the experimental test phase. Thus, part of this project will aim at investigating whether turbulent flow noise can be predicted from mathematical theories and methods. This will be fundamental, as it directly relates to the problem of testing in smooth flow wind-tunnels.

## 3.2 Experimental Work:

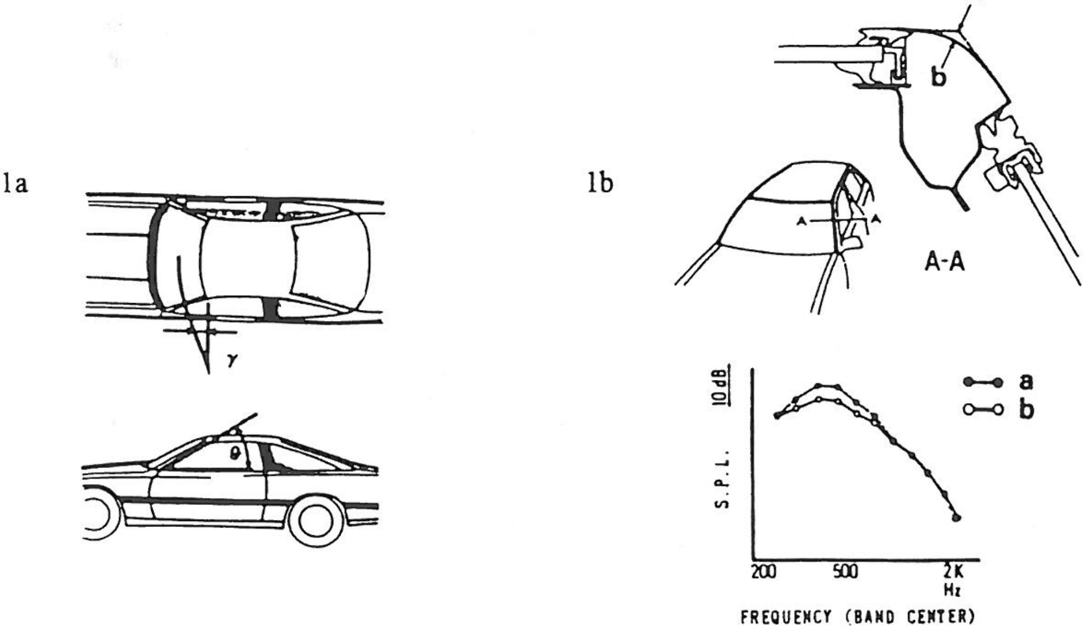
Research from the experimental view point has identified the main problems associated with aerodynamic noise in smooth flow and the resulting car interior noise. Extensive investigations by *Dobrzynski (1983)* have shown the dominance of local flow separations in causing rather large pressure fluctuations on the car body surfaces, which in turn are responsible for structural car-body excitation and hence vibrations and noise. The most crucial areas of interest are the A-pillar section (see Figures 1a & 1b) and side windows of the car. Separations and vortical flows in this area are the dominant sources of turbulent flow noise and are to be avoided for minimum interior noise. This is however not always practical, as conflicts may arise between the optimum acoustic configuration of the vehicle and requirements of other essential engineering aspects involved with the car-body exterior design.

The need for testing in a representative turbulent environment becomes apparent, as the local flows around the A-pillar and side windows will most certainly be perturbed by unsteady oncoming flow, changing the strength and intensities of the turbulence as it varies in time and location in this area. The surface pressure fluctuations and flow noise in this region were also shown to be very sensitive to oblique flow incidences, *Dobrzynski et al (1994)*. The unsteady flow conditions thus need to be well defined, if on-road testing and conditions are to be complemented and predicted by wind-tunnel modelling.

### 3.3 Practical Aspects of Car Design:

Practical measures to reduce the interior noise have been implemented in modern production cars over the past decade, as a direct result from Dobrzynski's research. The prime aspect of car shaping and design is flush body surfaces. Flow separations are to be avoided at all times, so absence of perturbations is desired at the A-pillar region. Inclination angles of the windshield and side windows are also relevant to the flow being diverted around the corner of the A-pillar (see Figure 1a), which then governs whether or not the flow separates off the side window, and if indeed a conical vortex will form. Extreme attention is paid to the detail design of the A-pillar region and the rubber sealing around the doors and windows, which are not only to stop rain and dirt from entering the vehicle cabin, but also leakage (fluid mechanic and acoustic) and air flow induced cavity resonances. Currently, the rubber seals add significantly to the overall cost of the vehicle (frequently, triple sealing has to be employed to reduce wind noise), hence understanding and reducing the noise at the source is desirable.

Figure 1: Effect of front pillar detail shape on wind noise characteristics.
(reproduced from Sadakata et al , 1988.)



### ***4. TESTS TO DATE:***

Initial acoustic testing of Australian production family cars has revealed a noticeable difference in interior noise levels when looking at different models and makes. Corporate sensitivity does not allow mention of names and models at this stage, but it can be generally stated that a luxury version family sedan was considerably quieter on the road at high speeds than a baseline model in similar on-road conditions. This can most likely be attributed to the better quality and higher quantities of sound absorbing materials, better manufacturing and finish of the rubber sealing. These cars have also been tested in the new RMIT/Monash University full-scale wind-tunnel, where similar conclusions were drawn. This has proven to be a valuable exercise, as it showed quite clearly many differences in interior noise from a wind-tunnel environment to the on-road case, such as the intermittency of wind gust noise. The major problem in the on-road situation was found to be the rolling tyres and often poor road surface conditions, introducing extraneous noise components. In the wind tunnel, the comparatively small component of tunnel-generated noise was far less noticeable inside the car than the extraneous components on the road, hence giving encouraging signs for future work in this area, as the air flow noise component was clearly dominant in this situation. On-road tests were performed which as yet have not been evaluated for further presentation, but some general conclusions can be mentioned. The turbulence intensity experienced by the vehicle on the day of testing was very high due to gusty strong winds of up to 15 $ms^{-1}$. Initial estimates of turbulence experienced by the vehicle put the figure at around 8-10%. Car speed, yaw angle and gust strength had the most influence on the perceived noise. Speeds of 140 km/h and a yaw angle of about $20^o$ gave the loudest wind noise inside the car cabin, as perceived by the driver.

In the near future, further on-road tests are planned in order to more accurately determine the air flow turbulence characteristics in the A-pillar and side window region, via the use of multi-component hot-wire anemometers. Simultaneous interior noise measurements will shed light on the main questions concerning the turbulence effects on the vehicle interior noise.

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**APPENDIX:** *Lighthill's Stress Tensor and Inhomogeneous Wave Equation respectively:*

$$T_{ij} = (p - c^2\rho)\delta_{ij} + \rho u_i u_j + \tau'_{ij} \quad ; \quad \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

where:
$\rho u_i u_j$ = unsteady Reynold's stress, the most influential term in Tij
$(p-c_o^2\rho)\delta_{ij}$ = effects of heat conduction, negligible for low Mach number flows
$\tau'_{ij}$ = viscous shear stress, generally very small when compared to the Reynold's stresses experienced by vehicles and buildings
c = speed of sound in the medium; for air at sea level = 340m/s
p = p(x,t) = fluctuating pressure component
$\nabla$ = divergence operator