Cobra Probe Reference List with Abstracts

CARLINO, G., CARDANO, D. & COGOTTI, A. (2007) 'A new technique to measure the aerodynamic response of passenger cars by a continuous flow yawing' in *Vehicle Aerodynamics 2007, SP-2066*, (SAE 2007-01-0902), Society of Automotive Engineers - International, Warrendale, PA.

Abstract: A comprehensive treatment of a new technique to measure vehicle aerodynamic response under side wind conditions is presented. In opposition to the traditional measurement technique of yawing the vehicle by rotating the turntable, the flow itself is continuously deflected by the Pininfarina Turbulence Generation System (TGS), while keeping still the vehicle under investigation. By using this new technique it is possible to assess the dynamic behaviour of vehicles, with particular regard to side forces and yawing moment, in more realistic unsteady conditions opposed to the static setup of traditional measurements.

In the first part of this work, the unsteady flow, generated by the TGS, is characterized both by means of 4-hole Cobra Probe and stereo PIV measurements in empty and non-empty wind tunnel configuration. Some data acquired on the road will also be shown and compared with wind tunnel measurements. In the second part, the different wind tunnel setups will be used to test various vehicles in the wind tunnel, and the results will be compared with traditional wind tunnel measurements. The results obtained show a dynamic behaviour which significantly varies with the yawing frequency of the oncoming flow. This technique allows to investigate vehicle behaviours which are overlooked in traditional wind tunnel measurements, and to establish closer links with on road tests.

LINDENER, N., MIEHLING, H., COGOTTI, A., COGOTTI, F. & MAFFEI, M. (2007) 'Aeroacoustic measurements in turbulent flow on the road and in the wind tunnel' in *Vehicle Aerodynamics 2007, SP-2066*, (SAE 2007-01-1551), Society of Automotive Engineers - International, Warrendale, PA.

Abstract: Aeroacoustics of road vehicles is becoming more and more important as it directly affects the comfort of the passengers. The tests made in the wind tunnel, in low-turbulence flow conditions, show results that are qualitatively different from those measured on the road. To get a better understanding of this, Audi and Pininfarina decided to carry out a test campaign on some cars, both on the road and in the wind tunnel, in various turbulent flow conditions. In the case of road measurements, some typical turbulent flow conditions, like those caused by atmospheric wind and those produced by traffic, have been investigated.

Wind tunnel measurements have been performed both in the base wind tunnel (in Audi and in Pininfarina) and in the presence of turbulent flows generated, in the Pininfarina wind tunnel, by the Turbulence Generator System, already described in previous SAE papers. The turbulence of the flow that affects the cars was measured, both in the wind tunnel and on the road, by two Cobra Probes, while the internal noise of the car was measured by artificial heads, Cortex or Head Acoustics. The results are described in detail in the paper and show that some turbulence and noise conditions measured on the road are similar to those reproduced in the wind tunnel by the TGS. Moreover, a first subjective analysis of the noise measured on the road has been made. Some preliminary results are reported in the paper.

WATKINS, S., MILBANK, J., LOXTON, B.J. & MELBOURNE, W.H. (2006) 'Atmospheric winds and their implications for microair vehicles', *AIAA Journal*, **44** (11): 2591-2600.

Abstract: Major challenges to low speed micro flight are the transient and time-averaged velocities arising from the Atmospheric Boundary Layer (ABL), particularly turbulence a few metres above the ground. In this paper, prior work on the temporal and spatial characteristics of the ABL close to the ground, and the relative turbulence as perceived by a moving craft, is considered. New measurements are described that document the time-averaged and transient velocities at a height of 4 m above the ground. These were made using a bank of four multi-hole pressure probes laterally separated by 150 mm and 50 mm on a mast above a test car. Transient flow pitch angles were investigated and it was found that the overall variation with lateral separation decreased relatively slowly with reducing separation, but that both this and the pitch angle coherence may be described non-dimensionally. As the slow decrease in pitch variation with lateral spacing implies that the roll inputs arising from vertical fluctuations would increase with reducing span, it is speculated that increasingly active and authoritative control systems are required.

NG, E., WATKINS, S. & JOHNSON, P. (2004) 'New pressure-based methods for quantifying radiator airflow', *Proc. Instn Mech. Engrs, Part D: Journal of Automobile Engineering*, **218**: 361-372.

Abstract: The high-complexity of vehicle front-end design, arising from considerations of aerodynamics, safety and styling, causes the airflow velocity profile at the radiator face to be highly distorted, leading to potentially reduced airflow volume for heat dissipation. A review of the existing experimental techniques for quantifying radiator airflow indicates that currently the most commonly used methods in the automotive industry are propeller based, despite the fact that the accuracy is in doubt, especially when documenting detailed airflow distributions. Two relatively new techniques, including a four-hole dynamic pressure (Cobra) probe and a new pressure based technique, are presented in this paper. The Cobra probe featured a head size of 1.2 mm and was used to document flow fields in proximity to a section of radiator core in a wind tunnel. The results show that the flow field at the radiator core exit was extremely complex, consisting of jets and wakes. In an investigation of the effect of airflow maldistribution on radiator heat-transfer performance, a newly developed pressure-based technique was implemented for the measurement of radiator airflow distribution. This technique, based on relating local airflow pressure drop through the radiator core to local velocity, is also discussed in the paper. The advantages of the technique over the existing methods include simplicity, robustness and relative insensitivity to air temperature thus making the technique suitable for use in complex, thermally stratified flow fields.

MALLIPUDI, S., SELIG, M. & LONG, K. (2004) 'Use of a four-hole Cobra pressure Probe to determine the unsteady wake characteristics of rotating objects', In *24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 28 June - 1 July*, Portland, Oregon, American Institute of Aeronautics and Astronautics, AIAA 2004-2299.

This paper investigates the wake characteristics of rotating static objects, typical of US Navy ship emitters, using a four-hole Cobra Probe. The Cobra Probe has the ability to measure unsteady 3D velocity. An in-situ calibration was performed and compared to manufacturer specifications. Agreement between the in-situ and manufacturer calibrations led to a practical assessment in a 3D turbulent flow field. The assessment provided insight into the wake of rotating and static objects, and further explored limitations and advantages of the Cobra Probe for subsonic wake flows.

MALLIPUDI, S. (2004) 'Determination of rotating object wake characteristics with application to the US Navy', MSc thesis, Aerospace Engineering, University of Illinois, Urbana-Champaign, USA.

COCHRANE, L. (2004), 'New developments in commercial wind engineering', Invited paper in *International Workshop on Wind Engineering & Sciences, Oct 2004*, New Delhi, India.

CHEUNG, J.C.K., EADDY, M. & MELBOURNE, W.H. (2003) 'Wind tunnel modelling of neutral boundary layer flow over mountains' in *Proceedings of the 11th International Conference on Wind Engineering*, Lubbock, Texas, ed. K. C. Mehta: 2837 to 2844.

Abstract: Wind tunnel experiments have been carried out in the 12m wide by 4m high working section of the 1.5MW wind tunnel at Monash University to measure turbulent wind flow downstream of a 1/200 scale model of a 334m high mountain. Three component wind velocities, turbulence intensities and Reynolds shear stresses have been measured behind the mountain with the approaching neutral boundary layer flow of a tunnel gradient wind speed 10ms-1 to study flow interactions with topography. The wind flow was found to have separated on the leeward side of the mountain around the two sides and over the top causing significant flow distortion and orographical induced turbulence. These changes due to the flow separation in the wake region of the mountain can have further impact on the wind-induced response of structures downstream. Finally some measured data are included for the wind flow characteristics behind a similar mountain model of a smaller geometric scale of 1/1500 for comparison.

EADDY, M., MELBOURNE, W.H. & SHERIDAN, J. (2003) 'Cross wind forces on rough circular cylinders in turbulent flow' in *Proceedings of the 11th International Conference on Wind Engineering*, Lubbock, Texas, ed. K. C. Mehta: 2461-2468.

Abstract: Sectional fluctuating lift force and lift axial correlation length measurements on large rough cylinders in turbulent flows have been performed for Re = 1 x 10^5 to 1.4 x 10^6. The presence of surface roughness was found to increase the lift axial correlation length and to enhance the effect

of free stream turbulence. Free stream turbulence was found to increase the sectional fluctuating lift force whilst the inherent three-dimensionality reduces the lift axial correlation length. The combination of these effects cause the high total lift forces experienced by rough cylinders in turbulent flow.

HOLMES, J.D. (2003) 'Emerging issues in Wind Engineering - Part 2' in *The Wind Engineer*, newsletter of the American Association for Wind Engineering (AAWE), Fort Collins, CO, USA, Sept**:** 1-8.

STEPHENS, A., WATKINS, S. & DIXON, C. (2003) 'Aerodynamic testing of a vented disc brakes' in *SAE Technical Paper Series*, Society of Automotive Engineers - International, Warrendale, PA, SAE 2003-01-0932.

VINO, G., WATKINS, S. & MOUSLEY, P.D. (2003) 'The passenger vehicle wake under the influence of upstream turbulence' in *Vehicle Aerodynamics, SP-1786*, (SAE 2003-01-0650), Society of Automotive Engineers - International, Warrendale, PA.

WATKINS, S. (2003) 'Development of a micro air vehicle', *The Aeronautical Journal*, February, **107**(1068): 117-123.

Abstract: The aerodynamic characteristics of five planar flying wing planforms suitable for micro air vehicles (MAVs) are investigated via a series of wind-tunnel tests. The external boundary of the five planforms result from slender carbon fibre (CF) struts under various degrees of buckling. The maximum lift/drag ratios were similar for all the (quite different) shapes but the stall characteristics were found to be markedly different. Results are presented of cross-plane traverses detailing the wake vector field and turbulence characteristics for two of the planforms at conditions close to stall. A MAV, based on mylar-covered buckled CF struts, is described. The MAV utilises elevon control based on modified commercially available micro radio control systems.

BENNETT, L. (2002) 'Modelling and Testing of Air Flow in an Automotive Air Conditioning System', MEng thesis, Mechanical & Manufacturing Engineering, RMIT University, Melbourne, Australia.

BENNETT, L., DIXON, C. & WATKINS, S. (2002) 'Modelling and testing of air flow in a HVAC module' in *Vehicle Aerodynamics, SP-1679*, (SAE 2002-01-0506), Society of Automotive Engineers - International, Detroit, USA.

Abstract: Airflow through an automotive air conditioning unit was mathematically modelled and validated using data from an experimental model. The domain of the model was limited to the HVAC module, including the heater and evaporator cores, subsequent mixing chamber and outlet ducting (which was of a simplified geometrical nature). The blower fan and scroll were not included and instead replaced, in the experimental and theoretical models by a fully developed flow entering the HVAC through a straight duct. The Computational Fluid Dynamics (CFD) code FLUENT 5.0 was used as the basic mathematical modelling tool.
Overall, the CFD model predictions showed the same trends as the experimental model at the outlets and across selected internal planes although some of the CFD predictions were outside the desired tolerance level when compared to the measured data. Nevertheless, considering the very torturous paths imposed on the airflow by the compact nature of the HVAC module, the level of predictive accuracy achieved was encouraging. It is felt that, with the level of modelling complexity adopted here, useful exploration of design alternatives can be carried out using CFD to indicated the likely nature of changes to the flow. Absolute values of flow parameters for final design decisions should be established by confirmation with experimental measurements on prototype HVAC modules.

EADDY, M., MELBOURNE, W.H. & SHERIDAN, J. (2002) 'Crosswind force on rough circular cylinders in turbulent flow' in *Proceedings of the 55th Annual Meeting of the Division of Fluid Dynamics, Dallas, Texas, Nov 2002*, American Physical Society, **47**(10): [Abstract only].

Abstract: Previous investigations have shown that the presence of surface roughness and free stream turbulence increases the total crosswind force experienced by a circular cylinder at Reynolds numbers greater than 2 x 10^5. The present study investigates the influence of these factors on the sectional lift force and the axial correlation of the lift force. Experiments were conducted in a wind

tunnel over a Reynolds range of 2 x 10^5 to 1.4 x 10^6. Surface roughness was created using sandpaper, and the free stream turbulence was generated using grids upstream of the cylinder. The sectional lift force was determined by integrating the instantaneous pressure distribution around the cylinder at mid span. The axial correlation was calculated by cross-correlating the pressures along the 90 and 270-degree generators (0 degree being the front stagnation line). The results indicate that the sectional fluctuating lift force is influenced by the turbulence intensity, and that the axial correlation is influenced by the relative surface roughness. Comparison is made with smooth cylinders for similar and higher Reynolds numbers.

GILHOME, B.R. (2002) 'Unsteady and time-averaged near-wake flow over the rear of sedan automobiles', PhD thesis, Mechanical Engineering, Monash University, Melbourne, Australia.

GILHOME, B.R. & SAUNDERS, J.W. (2002) 'The effect of turbulence on peak and average pressures on a car door' in *Vehicle Aerodynamics*, *SP-1667*, (SAE 2002-01-0253), Society of Automotive Engineers - International, Detroit, USA: 225-235.

Abstract: The influence of turbulence on automotive aerodynamics requires further investigation. This paper provides evidence that turbulence directly affects average and peak forces on the front door of a sedan automobile. Wind tunnel and several on-road tests conditions were investigated. The results include instantaneous peak and average force coefficients, together with experimental pressure contour plots for a sedan front door.
The pressure distribution over the front door of an automobile is important for efficient structural and door seal design. Door pressure distributions vary with flow turbulence characteristics. The results presented in this paper show that turbulent properties of the flow are of importance when investigating flow over the front door of a sedan automobile.

GUO, Y. & WOOD, D.H. (2002) 'Measurements in the vicinity of a stagnation point', *Experimental Thermal and Fluid Science*, **25**: 605-614.

Abstract: This paper presents measurements of a plane jet impinging onto a normal flat plate placed up to five jet widths from the jet outlet. The small spacing ensured that the stagnation streamline remained in the potential core of the jet. The plate shear stress distribution compared well to that from an analytical solution for the laminar development of the plate boundary layer whose external velocity was determined from the measured pressure. By comparing the shear stress measured under the present low level of freestream turbulence (0.35%) at the jet exit with that of Tu and Wood [Exp. Thermal & Fluid Sci. 13 (1996) 364-373] made at about 4%, it is concluded that the turbulence level at the nozzle exit has only a second-order influence on the surface shear stress around the stagnation point. Some spanwise non-uniformity was observed in the plate shear stress, but this was confined largely to the transition region. The mean velocity, Reynolds stresses and flutuating pressure were measured along the stagnation streamline using a fast-response pressure probe. A significant increase in the streamwise normal stress and the mean square of the pressure fluctuations occurred before they were eventually attenuated by the plate. This increase occurred in the region where the streamwise velocity was decreasing close to the plate causing extra energy production through the normal stresses. Spectra of the velocity and pressure fluctuations showed that the increase in level was mainly due to the low frequency motion, whereas the subsequent decrease occurred at higher frequencies.

NG, E. (2002) 'Vehicle Engine Cooling Systems: Assessment and improvement of wind-tunnel based evaluation methods', PhD thesis, School of Aerospace, Mechanical & Manufacturing Engineering, RMIT University, Melbourne, Australia.

NG, E., WATKINS, S., JOHNSON, P. & MOLE, L. (2002) 'Use of a pressure-based technique for evaluating the aerodynamics of vehicle cooling systems' in *Vehicle Aerodynamics*, *SP-1667*, (SAE 2002-01-0712), Society of Automotive Engineers - International, Detroit, USA: 71-82.

Abstract: A pressure-based technique has been developed for the purpose of radiator cooling airflow measurement. The technique was effectively utilised to quantify the local time-averaged air velocity through radiator cores in a small wind tunnel. The pressure difference indicated by the technique was found to be a function of the normal component of the air velocity. This paper describes the development and use of the technique which is compact, robust and non-intrusive. By applying this technique, the airflow distribution across the radiator face has been measured for a

complete vehicle in an aerodynamic wind tunnel and in an environmental chamber. Results are compared for the different test environments. The influence of airflow distribution on Specific Dissipation (a parameter used for evaluating radiator cooling performance) is examined and results for propeller-based methods and pressure-based methods are compared. It is found that the pressure-based technique has given reliable results and can be a practical tool for use in evaluating the aerodynamics of vehicle cooling systems. In addition, this study also reveals a considerable lack of uniformity across the radiator front face of a typical passenger vehicle, inefficient use of the radiator core heat-transfer area with consequent.

WATKINS, S. (2002) 'Development of a micro air vehicle' in *Unmanned Air Vehicle Systems, Seventeenth International Conference, 8 - 10 April*, University of Bristol, Bristol, UK**:** 20-1 to 20-10.

Abstract: The aerodynamic characteristics of five planar flying wing planforms suitable for micro air vehicles (MAV's) are investigated via a series of wind-tunnel tests. The external boundary of the five planforms result from slender carbon fibre (CF) struts under various degrees of buckling. The maximum lift/drag ratios were similar for all the (quite different) shapes but the stall characteristics were found to be markedly different. Results are presented of cross-plane traverses detailing the wake vector field and turbulence characteristics for two of the planforms at conditions close to stall. A MAV, based on mylar-covered buckled CF struts is described. The MAV utilises elevon control based on modified commercially available micro radio control systems.

WATKINS, S., MOUSLEY, P.D. & HOOPER, J.D. (2002) 'Measurement of fluctuating flows using multi-hole probes' in *Proceedings of the 9th International Congress of Sound and Vibration, Orlando, Florida, USA, 8-11 July*, International Institute of Acoustics and Vibration (IIAV).

Abstract: Time-varying flows occur in many industrial situations and can be a major source of noise and vibration. The measurement of such flows is usually performed using optical systems, such as laser-Doppler anemometry and particle image velocimetry, or hot-wire anemometry. However, the nature of industrial flows is such that more robust instrumentation is desirable, and recently dynamically calibrated multi-hole pressure probes have been utilized. The probes utilize facetted faces that have pressure taps linked to differential pressure transducers via thin tubing and have been miniaturized to 1.6 mm head size. A head calibration is performed initially, where the probes are oriented at various angles to known steady airflows thus mapping out surfaces that describe the steady-state response to velocity. The maximum frequency response (of up to 1,500 Hz) is obtained utilizing dynamic calibration. This paper describes the probes and their typical uses. Automotive and aeronautical applications are described, including measurements of atmospheric turbulence experienced by the moving vehicle and how it relates to aerodynamically generated in-cabin car noise, the steady state and transient airflow through vented disc brake rotors and how the probe has been utilized to map out turbulent flow parameters (eg Reynolds stresses) in the wake of micro air vehicles.

ALAM, F., WATKINS, S., ZIMMER, G. & HUMPHRIS, C. (2001) 'Effects of vehicle A-pillar shape on local mean and time-varying flow properties' in *Vehicle Aerodynamics, SP-1600*, (SAE 2001-01-1086), Society of Automotive Engineers - International, Warrendale, PA: 265-275.

Abstract: Separated flow is the main generator of aerodynamic noise in passenger vehicles. The flow around the A-pillar is central to the wind noise as many modern vehicles still have high fluctuating pressures due to flow separations in this region. Current production vehicle technology

GILHOME, B.R., SAUNDERS, J.W. & SHERIDAN, J. (2001) 'Time averaged and unsteady near-wake analysis of vehicles' in *Vehicle Aerodynamics Design and Technology, SP-1600*, (SAE 2001-01-1040), Society of Automotive Engineers - International, Detroit, USA: 191-208.

Abstract: From an experimental investigation of a notchback car near-wake, a new topological structure for the wake is proposed. Although experiments were only conducted on notchback vehicles, the topology can be related to other car shapes. The unsteady behaviour of the near-wake was investigated. The near-wake frequencies, which can affect ride and steering comfort, were found to be 0.11U/Xr and 0.42U/Xr (Xr - reattachment length). The lower frequency appears to be a result of large scale vortex shedding ('hairpin' vortex) behind the backlight/rear-window. The higher frequency can be attributed to the shear-layer vortices.

GUO, Y. & WOOD, D.H. (2001) 'Instantaneous velocity and pressure measurements in turbulent mixing layers', *Experimental Thermal and Fluid Science*, **24**: 139-150.

Abstract: This paper presents a comprehensive comparison of the mean velocity and turbulence measurements from a four-hole pressure probe, also known as a Cobra probe, and an X-probe in plane mixing layers. The objective is to validate the measurement accuracy of the Cobra probe in a flow where the turbulence reaches high levels, but whose properties are well known. The comparison is made for the mean velocities, Reynolds stresses, triple products, and spectra, and demonstrates that the Cobra probe has reasonable accuracy for some of these quantities, such as the mean streamwise velocity and primary shear stress, but not for the others, such as the mean normal velocity. The correlation of the pressure and streamwise velocity, measured by the Cobra probe, behaves correctly in the potential flow. However, the correlation of the pressure and the cross-stream velocity, which appears in the transport equation for the turbulent kinetic energy, and the pressure redistribution term in the corresponding equation for the streamwise normal stress, are poorly measured.

HOOPER, J.D. & WATKINS, S. (2001) 'Mean velocity, Reynolds stress and static pressure measurements in an air cyclone' in *Proceedings of the 14th Australasian Fluid Mechanics Conference, Adelaide University, Adelaide, Australia, 10-14 December*, Causal Productions, Adelaide, Australia.

Abstract: The flow field in a gas cyclone with no particulate load was documented using a dynamic Cobra pressure probe. The six Reynolds stresses as well as the time-averaged velocity vectors were mapped for nine stations. A relatively low turbulence level vortical flow was found in the outer regions of the cyclone body but high turbulence levels were measured below the vortex finder, although here the mean tangential velocity distribution was well defined as solid body rotation. The time-averaged results were in fair agreement with a numerical study and further work is planned with a low particulate load in the flow.

MOUSLEY, P.D., WATKINS, S. & O'SHEA, P. (2001) 'Modulation of in-cabin car wind noise by atmospheric winds' in *Proceedings of the Eighth International Congress on Sound & Vibration*, The International Institute of Acoustics and Vibration (IIAV), Hong Kong.

Abstract: A program to uncover links between fluctuations in atmospheric winds and the modulation of vehicle interior noise has been undertaken at RMIT University. It is widely accepted that fluctuating noise annoys vehicle occupants more than constant noise. However, most aeroacoustic development of passenger vehicles is conducted in low-turbulence wind tunnels that do not simulate atmospheric turbulence that is responsible for much of the aeroacoustic noise fluctuation. It is hoped that the program undertaken by RMIT will enable synthesis of 'real world' wind noise from recordings obtained in smooth flow wind tunnels.

In this paper, an introduction to the complex interactions between the wind environment and interior noise is provided, along with a brief discussion of the problems associated with evaluating a vehicles noise performance in gusty wind conditions. Examples of links that have been found to exist between wind fluctuations and modulation of interior noise, and the methods used to obtain these links, are presented.

NG, E., WATKINS, S., JOHNSON, P. & MOLE, L. (2001) 'Measuring local time-averaged airflow velocity through an automotive heat exchanger' in *Proceedings of the 14th Australasian Fluid Mechanics Conference, Adelaide University, Adelaide, Australia, 10-14 December*, Causal Productions, Adelaide, Australia.

Abstract: In some applications, the airflow in an air-cooled cross-flow compact heat exchanger is complex and non-uniformly distributed. The present study reveals the considerable lack of uniformity across the radiator air face for typical automobiles. This paper presents the development of an experimental technique for measuring the local time-averaged airflow velocity through radiators. Test results using a full-scale vehicle tested in a wind tunnel are presented, including flow visualisation around the radiator and contour plots of the velocity distribution over the radiator core.

WATKINS, S., MOUSLEY, P.D., MILBANK, J. & ALAM, F. (2001) 'Aeroacoustic noise and the motor vehicle: Research at RMIT University', *Acoustics Australia*, December 2001, **29**(3): 111-115.

Abstract: With every new model of car, customers expect reductions in noise and increases in refinement. Aeroacoustic noise plays a significant role in reducing the perception of quality of a

vehicle and thus vehicle manufacturers now place a high priority on reducing this noise. In this paper, an overview of the common aeroacoustic nosie sources in vehicles and the research being conducted at RMIT University to better understand and reduce aeroacoustic noise, is discussed.

WATKINS, S., RIEGEL, M. & WIEDEMANN, J. (2001) 'The effect of turbulence on wind noise: A road and wind-tunnel study' in *Automotive and Engine Technology, 4th Stuttgart International Symposium, 20-22 February*, eds. M. Bargende & J. Wiedemann, expert verlag, Stuttgart, Germany, **2:** 326-340.

Abstract: The temporal nature of in-cabin wind noise heard whilst driving is not generally reproduced in wind tunnels, since turbulence arising from the atmosphere and wakes of other vehicles are not simulated. For this work, turbulence was generated in the IVK Wind Tunnel, either by means of a large plate in the settling chamber or a small car placed in the nozzle exit. In-cabin noise and external flow properties were measured for a test car under the above conditions and also on-road. Whilst similar turbulence intensities to those measured on-road were measured in the tunnel, acoustic spectra showed little difference between the test conditions, although subjectively the sounds were different. Modulation analysis (a type of time-frequency analysis) revealed the temporal nature of the sound. It was concluded that further emphasis be placed on developing methods to more closely represent the nature of the human auditory system to temporal fluctuations and for simulating the real flow environment in wind tunnels.

ZIMMER, G., ALAM, F., WATKINS, S. & PERIC, C. (2001) 'Comparison of high blockage wind tunnel, open jet wind tunnel and on-road testing with respect to exterior surface pressures' in *Vehicle Aerodynamics, SP-1600*, (SAE 2001-01-1087), Society of Automotive Engineers - International, Detroit, USA: 277-284.

CHEN, J., HAYNES, B.S. & FLETCHER, D.F. (2000) 'Cobra probe measurements of mean velocities, Reynolds stresses and higher-order velocity correlations in pipe flow', *Experimental Thermal and Fluid Science*, **21**: 206-217.

Abstract: This paper is concerned with the validation of a four-hole pressure probe, known as a Cobra Probe, for turbulence measurement. For the first time in the literature, third- and fourth-order velocity correlations measured using a pressure probe are presented. The probe measurements are compared with established data for fully developed pipe flow, and good agreement is found. A new probe calibration methodology and improvements to the data acquisition and processing system are also presented.

MILBANK, J., WATKINS, S. & KELSO, R. (2000) 'Development of a small-scale aeroacoustic open jet, open return wind tunnel for cavity noise and component testing' in *Vehicle Aerodynamics, SP-1524*, (SAE 2000-01-0867), Society of Automotive Engineers - International, Detroit, USA: 195-206.

Abstract: A small-scale aeroacoustic wind tunnel has been designed and built to investigate tonal cavity noise in the frequency range applicable to passenger vehicles; 1 - 16 kHz. The tunnel is required for testing associated with an investigation into tonal cavity noise on passenger-vehicle wing mirrors. It was designed to operate in the low subsonic speed range (60 - 140 km/h) with a nozzle exit cross-sectional area of 0.02 m2 and a 4:1 aspect ratio. The design was intended to achieve a smooth, quiet flow facility. In this paper the design process is summarised and the factors leading to particular design decisions are detailed. An initial evaluation has shown that only minimal changes are required to achieve very smooth, even flow at the nozzle exit at all required test speeds. The acoustic design needs further work as there is a significant amount of flow noise at the nozzle exit between 1 and 13 kHz. Tests of a rearview mirror on-road and in a full-size wind tunnel indicated the background noise levels required and results of these tests are included in this paper. Further work to reduce background noise is proposed.

MOUSLEY, P.D. & WATKINS, S. (2000) 'A method of flow measurement about full-scale and model-scale vehicles' in *Vehicle Aerodynamics, SP-1524*, (SAE 2000-01-0871), Society of Automotive Engineers - International, Detroit, USA: 263-271.

Abstract: High-frequency pressure probes were used to map the airflow around a full-scale truck during on-road testing and around a model-scale truck during wind tunnel testing. Several configurations were tested during each type of testing. Results are presented for on-road 'pass-by' tests and detail velocity and coefficient of pressure variation alongside the truck at different heights. The wind tunnel data are results of flow mapping about a 10% scale model and show the velocity

and coefficient of pressure distribution under and around the model truck for different configurations.

SAUNDERS, J.W. & MANSOUR, R.B. (2000) 'On-road and wind tunnel turbulence and its measurement using a four-hole dynamic probe ahead of several cars' in *Vehicle Aerodynamics, SP-1524*, (SAE 2000-01-0350), Society of Automotive Engineers - International, Detroit, USA: 5-24.

Abstract: On-road measurements combined with a review of the literature suggest that it is rare for cars to travel in turbulence intensities less than 1%. It is typically 3%-5%. In an open, unobstructed environment, the length scale ranges from 2 - 17 m (average = 7 m). Alternatively, the presence of upstream motor cars reduce the length scales to 0.5 - 1.5 m (average = 1.2 m), but the cars increase the turbulence intensity from 5% to 20%. The placement of a similar size car one body length upstream in a wind tunnel presents an environment for aero-acoustic noise testing and perhaps other aerodynamic testing that is more typical of average freeway conditions than is normally found in most wind tunnels.

OSWALD, G. (1999) 'Influence of aerodynamics on the operating performance of automotive external rear view mirrors', PhD thesis, Department of Mechanical & Manufacturing Engineering, RMIT University, Melbourne, Australia.

Abstract: Over the recent decades extensive engineering efforts have been spent to reduce the noise and vibration levels experienced by the occupants of a modern motor car. The customers continue to demand higher levels of comfort and safety. The external mirror of an automobile is required to provide visual information to the driver and any vibration of the mirror glass may not only be annoying to the driver but can effect safety. Further, the mirror is located in an area of the vehicle that is known to produce aerodynamically generated noise and its shape is considered to influence the noise.

In the work presented, the effects of aerodynamics on the noise and vibration of an external rear view mirror for a typical mass produced family saloon vehicle was investigated.
Vehicles were equipped with miniature accelerometers on the mirror glass to measure the rotational vibration of the glass surface as the rotational vibration directly impacts on the image reflected to the driver. Hot-wire anemometers were also used to measure the characteristics of the airflow approaching the mirror and the vehicle interior noise was measured using an artificial head and a conventional sound level meter.

Measurements of the vibration levels experienced during normal operation at approximate highways speeds were taken on typical roads. This then enabled a comparison with values gathered from wind-tunnel testing where the vibration levels were generated from only the aerodynamic loads. By use of a wind tunnel the vibration levels, characteristics of the airflow approaching the mirror (at two mirror spanwise locations) and the interior noise could be measured for various vehicle yaw angles.

It was found that the mirror vibration level and approaching airflow are significantly affected by the vehicle yaw angle. In the controlled environment of the wind tunnel there was a large difference in the vibration level of the leeward and windward mirror glass at all speeds. This lead to the conclusion that the aerodynamically induced vibrations were produced mainly by buffeting of the housing or variations in base pressure acting directly on the mirror glass and not from vortex shedding from the inherently bluff mirror housing. The results indicated that worthwhile mirror development work can be conducted in a wind tunnel in the absence of the mechanical inputs (ie. from the road surface, engine or drive chain) as at a given speed the rotational vibration levels measured on the road could be closely reproduced in the wind tunnel.

The airflow characteristics showed a high level of turbulence in the approach airflow on the leeward side of the vehicle and almost freestream conditions on the windward side. The variations in the mean local flow and pitch angles can be considerable (as a function of location and car yaw angle). As these variations have been shown to significantly affect the mirror glass vibration and to a lesser extent the aerodynamic noise, the mirror cannot be tested in isolation from the vehicle as the details of the forebody and A-pillar region will strongly influence the performance of the mirror.

CHEN, J., FLETCHER, D.F. & HAYNES, B.S. (1998) 'Validation of the cobra probe using turbulence measurements in a fully developed pipe flow' in *Proceedings of the 13th Australasian Fluid*

Mechanics Conference, 13 - 18 Dec, eds. M. C. Thompson & K. Hourigan, Monash University, Melbourne, Australia, **1:** 385-388.

Abstract: This paper is concerned with the validation of a four-hole pressure probe, known as the Cobra probe, for turbulence measurement. Here the probe measurements are compared with established data for fully developed pipe flow, and good agreement is found. Improvements to the data acquisition and processing systems, and probe calibration methodology are also presented.

GUO, Y., HOOPER, J.D. & WOOD, D.H. (1998) 'Instantaneous velocity and pressure measurements in a plane turbulent mixing layer' in *Proceedings of the 13th Australasian Fluid Mechanics Conference, 13 - 18 Dec*, eds. M. C. Thompson & K. Hourigan, Monash University, Melbourne, Australia, **1:** 35-38.

Abstract: This paper describes fast-response pressure probe measurements in the single stream mixing layer and potential core forming the initial region of a plane turbulent jet. Comparison with X-probe measurements of the mean velocities and Reynolds stresses shows that the new technique has a reasonable accuracy. Furthermore, the correlation of the pressure and the streamwise velocity behaves correctly as the potential flow is approached. These results demonstrate the probe's ability to measure the pressure-related quantities in the Reynolds stress transport equations such as the correlation of the pressure and the cross-stream velocity. This correlation is compared to the triple velocity products that appear with it in the turbulent diffusion of turbulent kinetic energy.

MOUSLEY, P.D., WATKINS, S. & HOOPER, J.D. (1998) 'Use of a hot-wire anemometer to examine the pressure signal of a high-frequency pressure probe' in *Proceedings of the 13th Australasian Fluid Mechanics Conference, 13 - 18 Dec*, eds. M. C. Thompson & K. Hourigan, Monash University, Melbourne, Australia, **1:** 395-399.

Abstract: The determination of both the fluctuating total and static pressures away from a wall in a turbulent flow field is difficult. In order to test the methodology adopted by the Cobra pressure probe to do this, the centre-hole fluctuating pressure signal of the four-hole pressure probe was used to measure the axial turbulent velocity component in a free jet, using a small signal approximation. This time dependant velocity was compared to the turbulent axial velocity component measured by a hot-wire anemometer, also located on the axis of the jet but 10 mm upstream of the Cobra probe head. Reasonable agreement was demonstrated between the two time dependant signals of the axial turbulent velocity.

HOOPER, J.D. & MUSGROVE, A.R. (1997) 'Reynolds stress, mean velocity, and dynamic static pressure measurement by a four-hole pressure probe', *J. Exp Thermal and Fluid Science*, **15**: 375-383.

Abstract: An improved version of the four-hole directional pressure probe, or Cobra probe, is described, in which the frequency response has been extended to 1.5 kHz. The probe measures all three orthogonal mean and turbulent velocity components at a point in a flow field. The probe also resolves the local mean and turbulent components of static pressure, allowing moments between the fluctuating velocity components and pressure to be determined. The techniques developed to allow the improved frequency response and the use of the probe in turbulent, developed pipe flow (a calibration flow) are described. Also given are the turbulent pressure-velocity correlations, which show a degree of anticorrelation for one velocity component.

SCHNEIDER, G.M., HOOPER, J.D., MUSGROVE, A.R., NATHAN, G.J. & LUXTON, R.E. (1997) 'Velocity and reynolds stresses in a precessing, deflected jet', *Experiments in Fluids*, **22**: 489-495.

Abstract: A novel fluid mixing device, described elsewhere, has been shown to have a dramatic effect on the combustion characteristics of a fuel jet. The main features of the flow are the deflection of the jet between 30° and 60° from the nozzle axis and its precession about that axis. Many of the factors governing the nozzle instabilities which drive the mixing in the external field are imprecisely defined. It is the aim of the present paper to examine, in isolation from the nozzle instabilities, the influence of precession on a deflected jet as it proceeds downstream from the nozzle exit. The fluid dynamically driven phenomena within the nozzle which cause the precession are in the present investigation replaced by a mechanical rotation of a nozzle from which is emerging a jet which is orientated at an angle from the nozzle axis. By this means the effect of precession on the deflected jet can be investigated independantly of the phenomena which cause the precession.

The experimental data reported here has been obtained from measurements made using a miniature, rapid response four-hole "Cobra" pitot probe in the field of the precessing jet. Phase-averaged three

dimensional velocity components identify the large scale motions and overall flow patterns. The measured Reynolds stresses complement the velocity data and are found to be compatible with the higher entrainment rates of the jet found in earlier investigations.

SCHNEIDER, G.M. (1996) 'Structures and turbulence characteristics in a precessing jet flow', PhD thesis, Department of Mechanical Engineering, University of Adelaide, Adelaide, Australia.

HOOPER, J.D. & MUSGROVE, A.R. (1995) 'Pressure probe measurements of Reynolds stresses and static pressure fluctuations in developed pipe flow' in *Proceedings of the Twelfth Australasian Fluid Mechanics Conference*, Sydney, Australia**:** 565.

HOOPER, J.D. & MUSGROVE, A.R. (1995) 'Pressure-velocity correlations in swirling pipe flow' in *Proceedings of the Twelfth Australasian Fluid Mechanics Conference*, Sydney, Australia**:** 557.

GUZMAN, D., FLETCHER, D.F. & HOOPER, J.D. (1994) 'Computational investigation of cobra probe operation', *Int J. of Numerical Methods for Heat and Fluid Flow*, **4**(5): 425-445.

Abstract: The detailed flow behaviour around a four-hole Cobra Pitot pressure probe, developed by the Commonwealth Scientific and Industrial Research Organization, Australia, (CSIRO), to determine the pressure and the velocity components in three dimensional single-phase/multi-phase fluid flow, is investigated computationally. The incompressible steady state Navier-Stokes equations are solved numerically using a general purpose computational fluid dynamics (CFD) code developed at CANCES. Computational results are presented for representative probe pitch and yaw angles at a Reynolds number = 2 × 103, emphasising the pressure distribution and flow separation patterns on the probe tip adjacent to the pressure ports. Quantitative comparison of the computational simulation to experimental results is done by comparing experimental calibration data to numerically computed pressure responses. The topological features of the near tip flow behaviour are visualised using critical point concepts and three dimensional streamlines. Additional qualitative comparison to experiment is discussed using data from a preliminary experimental investigation using surface oil film visualisation techniques, where available. Conclusions are drawn concerning the near tip flow behaviour, the good level of agreement between the numerical results and experimental data and the effectiveness of using a computational analysis to provide accurate detail useful for engineering design purposes.

SCHNEIDER, G.M., HOOPER, J.D., MUSGROVE, A.R., NATHAN, G.J. & LUXTON, R.E. (1994) 'Velocity and reynolds stresses in a precessing, deflected jet' in *Proceedings of the 2nd International Conference in Experimental Fluid Mechanics, July 4-8*, Torino, Italy.

MUSGROVE, A.R. & HOOPER, J.D. (1993) 'Pressure probe measurement of the turbulent stress distribution in a swirling jet' in *Proceedings of the 3rd World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, 31 Oct - 5 Nov*, eds. M. D. Kelleher, R. K. Shahet al, Elsevier Science Publishers, Honolulu, USA, **1:** 172-179.

Abstract: An improved version of a four-hole directional pressure probe (a Cobra probe) is described in which the frequency response has been extended to 1.5 kHz, sufficient to include most of the turbulent energy spectrum. The procedure for calibrating the probe to Mach 0.5, where compressible flow effects become significant, is described.

The probe can rapidly characterise a complex, high speed, turbulent flowfield. This paper reports all components of the mean and turbulent velocities, along with the Reynolds stress downstream of a swirling free jet. Unlike other methods, the Cobra probe also measures mean and dynamic static pressure, and is therefore capable of determining cross correlations between velocity and static pressure.

SCHNEIDER, G.M., VIDAKOVIC, S.S., HOOPER, J.D., MUSGROVE, A.R., NATHAN, G.J. & LUXTON, R.E. (1993) 'Theoretical and experimental pressure field evaluation downstream of a mechanically precessing jet' in *Proceedings of the 5th Australasian Heat and Mass Transfer Conference, December 6-9*, Brisbane, Australia.

HOOPER, J.D. & MUSGROVE, A.R. (1991) 'Multi-hole pressure probes for the determination of the total velocity vector in turbulent single-phase flow' in *Proceedings of the 4th International Symposium on Transport Phenomena in Heat and Mass Transfer*, ed. J. A. Reizes, Pacific Centre of Thermal-Fluids Engineering, Sydney, Australia, **4:** 1364.

Abstract: The calibration and response of a four-hole directional Pitot probe, in terms of the sensitivity of the probe to Reynolds number variation, and the limits on the yaw and pitch angles imposed by the probe geometry, is given to a maximum Mach number of 0.30. The use of the probe in a swirling duct flow with a highly turbulent wake region shows the probe to be a useful measurement system for use in industrial fluid mechanics problems.