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An investigation of aerodynamic noise exposure of motorcycle riders.

Kuldip Satsangi

University of Windsor

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UMI*
AN INVESTIGATION OF AERODYNAMIC NOISE EXPOSURE OF MOTORCYCLE RIDERS

By
Kuldip Satsangi

A Thesis submitted to the Faculty of Graduate Studies through the department of Mechanical Engineering in Partial Fulfilment of the requirements for the degree of Master of Applied Science at The University of Windsor

Windsor, Ontario, Canada
1977
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TO MY WIFE
ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Professor A. R. Howell for his supervision and guidance as well as continuous encouragement throughout the course of this study.

Thanks are also due to Dr. Z. Reif for his generous assistance in this study.

The assistance provided by the Industrial Research Institute and Mechanical Engineering Department for the facilities provided, as well as the cooperation from many of my fellow graduate students is gratefully acknowledged.

This study is a part of work performed for Transport Canada, contract number S3261-20-3.
"NOMENCLATURE"

A = Cross sectional area of the ear canal
A₁ = Empirical constant in Kings formula
B₁ = Empirical constant in Kings formula
\(c_p\) = Specific heat of air at constant pressure
d = Diameter of the hot wire sensor
d₁ = Tube diameter
f = Frequency
\(g_0\) = Gravitational Constant
I = Probe heating current
\(I_p\) = Probe current
\(I_b\) = Total bridge current
J = Joules constant
k = Probe calibration constant
L = Tube length
\(L_{eq}\) = Equivalent continuous sound pressure level
\(L'\) = Ear canal length
\(M_p\) = Microphone pressure response (\(mv/N/m^2\))
NIPTS = Noise induced permanent threshold shift
\(P_0\) = Mean pressure
\(P_l\) = Sound pressure exerted on diaphragm (dB.)
p = Ambient pressure
Q = Heat flux
R = Operating resistance of the hot wire
\(R_o\) = Resistance of hot wire at the fluid temperature
\(R/R_o\) = Resistance ratio
\(R_c\) = Cable resistance
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<td>$R_t$</td>
<td>Top resistance of 55M10 CTA =50Ω</td>
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<tr>
<td>$R_c'$</td>
<td>Reynolds number ( $\frac{d1+U}{V}$ )</td>
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<tr>
<td>$R'$</td>
<td>Distance of the source from the subject</td>
</tr>
<tr>
<td>$R''$</td>
<td>Ear canal terminal impedance</td>
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<tr>
<td>$R_i$</td>
<td>Thermometer recovery factor</td>
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<td>$R_x$</td>
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<td>Wire temperature</td>
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<tr>
<td>$T_o$</td>
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<td>$TTS_2$</td>
<td>Temporary threshold shift; measured two minutes after the cessation of noise</td>
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<td>$T_s$</td>
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<td>$T_i$</td>
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<td>$v_o$</td>
<td>Mean flow velocity</td>
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<tr>
<td>$V$</td>
<td>Bridge voltage</td>
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<td>$V_o'$</td>
<td>Bridge voltage at zero velocity</td>
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<td>$V_o$</td>
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<td>$v$</td>
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<td>$\Delta V_{out}$</td>
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<td>$w$</td>
<td>Angular velocity</td>
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<td>Pitot tube measurement uncertainty</td>
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<tr>
<td>$\alpha$</td>
<td>Overheating ratio</td>
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<td>$\gamma$</td>
<td>Kinemetic viscosity of air ( $\frac{P}{\mu}$ )</td>
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Nomenclature continued

\( \rho \) = Density of air at 300°K
\( \mu \) = Viscosity of air at 300°K
\( \lambda \) = Sound wavelength at 300°K
\( \delta v_n \) = Fluctuating velocity
\( \Delta \) = Uncertainty in measurements
SUMMARY

This study deals with the measurement of "at ear" aerodynamic noise levels at various flow speeds in a wind tunnel, with a full scale human head model; and its comparison with the noise levels received by live subjects in typical highway driving under similar conditions.

A suitable acoustical extension to the existing wind tunnel has been constructed and the background noise level reduced to 64 dBA.

The spatial distribution of sound pressure within the free stream has been studied as a function of free stream velocity at the test section. By suitable evaluation method, the tunnel noise has been divided into its contributing factors, viz. Sound Pressure Level generated by the C.F.Fan, aerodynamic noise and the velocity pressure fluctuations caused by both the mean flow turbulence and the turbulence generated by the model. An investigation has also been made into the directivity effect of sound incident upon the ear as a result of indexing the model in both horizontal and vertical plane and the effect of different visor shapes.

Suitable transfer functions have been obtained on the model, to perform pressure transformation on the recorded S.P.L.'s at cavum.
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Bruel and Kjaer Sound Level Calibrator Type 4230

Bruel and Kjaer Graphic Spectrum Equaliser Model 125

Bruel and Kjaer Level Recorder Type 2307

Bruel and Kjaer Beat Frequency Oscillator Type 1022

Bruel and Kjaer 2706 Power Amplifier

University Sound Model C.L.C. Weatherproof Hi-Fi Speaker

Bruel and Kjaer Generator Type 1405

Bruel and Kjaer Frequency Analyser Type 2107

Bruel and Kjaer Audio Frequency Spectrometer Type 2112

B&K Impulse Precision Sound Level Meter Type 2209

Measuring Amplifier - Bruel and Kajaer Type 2607

Statistical Distribution Analyser - B&K Type 4420

S.E. Eight-Four Portable Tape Recorder

Bruel and Kjaer 1"-Condenser Microphone Type 4145

B&K Half Inch Condenser Microphone #4134

Bruel and Kjaer Probe Microphone Kit UA 0040

B&K Piezoelectric Accelerometer 4333 with Voltage Preamplifier 2623

B&K Accelerometer Calibrator Type 4291

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Conclusion

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CHAPTER I

INTRODUCTION

1.0 Subject of Investigation

The present study deals with the assessment of aerodynamically generated noise due to the flow of wind over an exposed motor-vehicle operator. The need for the present study became apparent during the course of investigations of noise exposure of off-road vehicle riders being carried out in the department of Mechanical Engineering.

It has been found that wind generated noise becomes a significant contributor to overall noise when the vehicle speed is about 40 M.P.H. and above. Below this speed the noise spectrum consists of pure tones and harmonics generated by engine, exhaust and other parts of the moving vehicle. The wind noise has a broad band frequency spectrum which has a significant dependence upon the turbulence generated by the flow and body interaction. It has been found that the at-ear wind noise is in excess of 90 dBA. at a speed of 55 M.P.H. and a continuous exposure to this level may cause a shift in threshold of hearing. It should be recognised that even infrequent exposure to these sound pressure levels from a recreational vehicle may pose quite a significant risk of permanent hearing loss to those individuals.
who regularly engage in noisy leisure activities, or experience excessive noise exposure during employment and thus may already have had the maximum permissible noise dose.

Not enough studies have been performed on at-ear noise experienced by the operators of motor vehicles, such as motorcycles and snowmobiles; and those which exist, deal with the overall noise experienced at ear, and have not attempted to isolate the wind generated noise. Now since the maximum vehicle noise measurement method has been defined by the I.S.O. and S.A.E. stationary and passby test procedures, the noise emitted by the vehicle alone can be controlled within legal requirements but the rider may still be exposed to damaging noise levels at high speeds, due to the wind generated noise effect. In order to measure the S.P.L. at cavum for moving operators, ear-bug microphone was used instead of condenser microphone and preamplifier, because of its much smaller size, portability and very good frequency and directional response as discussed later. Unlike the condenser microphone, ear bug microphone does not alter the acoustic impedance of cavum due to its small size and hence the sound field is not disturbed by its presence in the cavum of the concha.

For the above reasons it was found necessary to investigate this area of aerodynamic noise generation to provide this fundamental information for use in noise exposure measurements on riders.

1.1 SCOPE:

The scope of the present study is limited to the following aspects:-

1. Construction of an acoustical extension to the wind tunnel with the necessary mounting and indexing facility for the model.
2. To reduce the ambient S.P.L. at the test section to the lowest possible value, with low turbulence levels and a nearly flat velocity profile across the test section.

3. To analyse the total sound field at the test section, and identify its sources.

4. To measure the wind generated noise at ear at various flow velocities, with and without the helmet and visor.

5. To study the effect of varying the angle of incidence of air flow on noise exposure.

6. To study the distribution of S.P.L. within the cavum and the effect of blockage of meatus on the pressure ratio between the cavum and the center head position in diffused field.

7. Measure the pressure transformation produced by the outer ear, using pure tones.
CHAPTER II

LITERATURE SURVEY

2.0 General:

The first part of this survey deals with the study of hearing damage risk criterion and measurement schemes. This is followed by the study of the theory of aerodynamic noise generation in fluid flows, followed by the study of propagation of sound in acoustically lined rectangular ducts. The fourth part deals with the study of various methods proposed, to differentiate between the pseudo noise and noise. The next part of the survey deals with the experimental and analytical investigations related to the present study; to be followed by a review of effective noise exposure of off-road recreational vehicle riders.

2.0.1 Hearing damage risk criterion and measuring scheme:

The undesired effects of noise on man's physical and subjective auditory response system have been fairly well studied and reported. Continuous excessive exposure to noise has been found to cause a temporary threshold shift of hearing, which becomes permanent if no recovery is allowed. It is customary to estimate the damage risk from prolonged exposure to steady state noise, by temporary threshold shift for pure tones from exposure to noise measured two minutes after the exposure (T.T.S2); and to call the shift as temporary, provided the hearing of the subject returns the preexposure levels within sixteen hours after the exposure.

Noise induced permanent threshold shifts (N.I.P.T.S.) are
the audiometric shifts measured with reference to the audiometric zero level, obtained from the preexposure audiograms; or if this information is not available, with reference to the audiometric zero defined by I.S.O. for normal healthy persons. This reference has to be adjusted for the presbycusis and sociocusis factors depending upon the age and the social environment of the person when applicable. The permanent threshold shifts are measured one month or so after the exposure to noise is stopped. It is estimated that NIPTS usually reaches its maximum value, depending upon the intensity of noise and its frequency composition, following up to 20 years or so of near daily exposure to a given noise environment. These two measures - TTS₂ and NIPTS, represent the fundamental data on which opinions regarding risks to hearing from exposure to a given noise are based.

As far as occupation noise being a hazard to the organ of hearing, studies of TTS are considered by some to be of academic interest because (a) no significant direct life long tests have been conducted with the same individual humans, and (b) susceptibility to TTS and NIPTS in some animals was not found significantly correlated although some studies indicate evidence to the contrary on human.

The presence of many influential factors within and without persons obviously make mandatory the need for a large number of subjects and a dependency upon statistical trends for getting answers to this problem area. Nevertheless, within the limitation of exposures up to 8 hrs. per day, the
following similarities between TTS and NIPTS upto 40 dB or so seem reasonably well established.

1: Exposure conditions that do not cause TTS in persons with normal hearing can cause no NIPTS when NIPTS exposure is defined as 10-20 years of 8 hrs. or less daily exposure.

2: Increasing the noise intensity above certain levels causes, within limits (upto no more than 40-50 dB.), a roughly similar increase in TTS and NIPTS.

3: The greatest amount of threshold shift from a given noise band occurs within one octave band above the frequency of the noise band for both TTS and NIPTS.

4: The frequency regions most susceptible to TTS are likewise most susceptible to NIPTS.

The TTS and NIPTS studies performed on different groups of people have been used by C.H.A.B.A.* working group to specify conditions for hazardous exposure to intermitant and steady state noise. In their specifications special allowance was made for the protection of frequency regions important to speech reception. The criterion proposed by C.H.A.B.A. group was that at least 50% of the people exposed nearly daily for 10 years to a noise environment should not suffer NIPTS. more than 10 dB at or below 1KHz, 15 dB at 2 KHz. and 20 dB or more at or above 3 KHz. It was estimated that the criterion would be met as the result of exposure of people to sound conditions specified by Damage Risk Contours (DRC.) as specified by C.H.A.B.A. group, and shown in Figure 1A-1.

Bostford^B found that 80 percent of some 75 noises

* C.H.A.B.A. : Committee on Health And Bio Acoustics.
from various manufacturing industries had relative levels in dBA that were the same as the relative levels of damage risk to be found by comparing the octave band levels of each of the noises with the D.R.C. It was concluded that 80 percent of the time one would get the same estimation of damage risk to hearing from dB(A) measures as from octave band measures of typical industrial noises. Thus it was suggested that overall dBA measures rather than octave band spectra of noises would often be adequate for estimating damage risk to hearing. With this assumption a new family of D.R.C. were developed (refer Figure 1A2) showing total duration of noise exposure allowed for an 8 hour day as a function of the number of periodic interruptions. This single number approach has been found to be very satisfactory in assessing the hearing damage risk.

Most environmental noise control bylaws and labor department requirements are specified in terms of Occupational Safety And Health Act (O.S.H.A.) regulation. The O.S.H.A. regulation specifies 90 dB(A) as the maximum permissible S.P.L. for 8 hours a day. A trade off of 5 dB(A) for each halving or doubling of daily exposure duration (i.e. 95 dB(A) for 4 hours or 85 dB(A) for 16 hours etc.) are specified. The apparent presumption of no hearing impairment with an average loss in hearing of 25 dB or less re-I.S.O. at 500, 1 kHz and 2 kHz and unlimited loss at frequencies above that, and the 90 dB(A) limit are the controversial features of the present occupational noise standards.
The dB(A) is a reasonably appropriate weighting for damage risk up to frequencies of about 2 kHz, but under-estimates relative damage risk to higher frequency bands. Since the wind noise energy, as most other industrial noises, tends to be confined in the low frequency range, and hearing losses above 2 KHz. are at present ignored in the formulation of damage risk, the use of dB(A) is considered adequate for most broad band noise measurements. However, dB(D) and dB(A) weightings are about equal at frequencies up to 1 KHz. and would therefore evaluate damage risk from broadband noise to hearing for frequencies up to 1 kHz equally well. In addition, dB(D) would more properly rate than would dB(A), damage risk to hearing at frequencies above 1000 Hz from noise that had its predominant energy at frequencies above 1 kHz.

In the present study, wind noise data has been gathered by the ear-bug, which has A-weighted output. In this way a permanent record of sound pressure level as a function of time has been obtained. Hence in contrast to the commercially available dosimeters, changes in sound levels, duration and temporal pattern can be determined for wind generated noise.

It is understood that the S.P.L. measured at the concha, is not the same as that existing at the same point in space, when the subject is removed. This results from several mechanisms, some dependent upon the geometry of the external ear and some on the position of the ear with respect to other parts of the body. In particular pinna
and concha introduce considerable pressure gains relative to free field values at frequencies between 1.5 and 7 kHz; and these contributions are very sensitive to the direction of the incident sound field. The torso and shoulders are also expected to interfere with the sound field reaching the ear, an effect that occurs at about 400-500 Hz. Thus to relate measurements at concha to existing schemes for hearing conservation, which usually assume the existence of a diffused sound field, observed in the absence of the subject, it is necessary to estimate the sound pressure at the centre head position. Thus with the microphone located at the cavum the sound pressure reaching the ear may be accurately monitored and a realistic allowance made for the body baffle effects on microphone response due to the presence of subject. This is however not possible with noise dosimeters.

In the present study at ear, wind noise measurements have been made with both earbug and dosimeter and the 'Leq' (equivalent continuous sound pressure level) have been compared. However, frequency transformation on this data has not been carried out to estimate sound pressure at centre head position in the absence of the rider.

2.1 Concept and theory of aerodynamic noise generation

Pressure variations inevitably occur in all unsteady flows. Sometimes these variations are confined to the flow itself, providing the volume force necessary to balance the fluctuations of local momentum, and sometimes they
propagate away from the flow as sound. Pressure variations can be recorded by ear or with a microphone and there is a tendency to regard all pressure sensed in this way as sound. A terminology has evolved that distinguishes the propagating and non-propagating pressure fields as sound and pseudo sound respectively. In a sound field, pressure fluctuation levels are of the order of $p c_0 \delta v$, while in a pseudo sound field they are $p \delta v^2$, being essentially independent of the sound speed $c_0$. The mean density is $p$ and local velocity fluctuation is $\delta v$. When the pressure fluctuations occur over a broad continuous frequency spectrum, they are regarded as noise, so that the subject of hydrodynamic noise encompasses all forms of broad band pressure fluctuations induced by unsteady flow or turbulence.

Ffowcs Williams has noted that the velocity field can be thought of as driven by a prescribed vorticity field. In this way one can attribute motions at some distance from a concentration of vorticity to that vorticity, responding immediately to any vorticity change. In the same way the pressure gradients bringing about the immediate response can be thought of as driven by the same concentration of vorticity. Two regions of pseudo sound can therefore be distinguished. The first is in and around the most active vorticity field, where the pressure is essentially locally determined. The second is that in the more remote regions that merely respond to the driving field. There the pressure can be thought of as driven...
from the source region in the vorticity field. This feature makes part of the field appear very much like sound and the influence of source propagates at the sonic speed; but in the pseudo sound field the distances involved are small enough and the slight acoustic time delay is a negligible fraction of the time scale in the fluid motion. This is no longer true if the distances involved are a significant fraction of an acoustic wave length, so that pseudo sound gives way to real sound at that distance.

The pseudo sound field most studied in recent years is that on the surface of a boundary supporting a turbulent boundary layer. Kraichnan showed that this field was influenced by the mean velocity gradients and the mean shear stress at the wall. Lilley and Hodgson greatly expanded Kraichnan's model and used measurements of the turbulent velocity field to show how the wall pressure was essentially determined in the relatively high speed region of the boundary layer somewhat remote from the wall. Shubert and Corcas showed that this conclusion could be exploited to give a very convincing argument that the flow in the immediate wall layer, far from generating the local pressure field was in fact driven by it. The pseudo sound field within the isotropic turbulence has been studied by Batchelor but very little work has been performed on the details of pressure fields within general shear flow turbulence. In all of these cases the pseudo sound pressure level was proportional to the dynamic head and at about
the same space and time scales as the turbulence itself, converting with those turbulent eddies that drive the field.

A lot of work has been done in predicting radiated sound field of an acoustic quadrupole, assuming that the sound field is an essential by-product of turbulence, the turbulence itself being uneffected by its presence. This viewpoint is justified by the experimental observations that a very small fraction of turbulent energy leaves the flow as sound.

Various investigators have performed acoustic measurements on flow models, of which Lighthills' acoustic analogy is most widely known. He has studied the radiation field of relatively small regions of turbulent flow embedded in an infinite homogeneous medium at rest; while neglecting the effects of reflection, diffraction, absorption or scattering by solid boundaries. This is however not true in our case where the radiation field is being studied under the surface supporting the turbulent boundary layer and is bounded by tunnel walls. Since the noise reaching the test section is dominated by the low frequency flow fluctuations, generating momentum fluctuations; our sound source is expected to be dipole.

Various extentions of Lighthills theory have been developed to predict diffused field noise levels of a source but hardly any literature could be found dealing with wind and surface interaction noise measured under the surface. Stapleford and Carr have studied the nature of
flow and noise spectrum at the surface of the automobile body, supporting a turbulent boundary layer. He has reported that significant variations in frequency spectrum exist between separated flow, vortex flow, re-attached and attached flow regimes.

2.2 Propagation of Sound in Acoustically Lined Ducts

In the course of study of basic properties of acoustic linings for ducts transmitting air at high speeds, experimental evidence from various studies indicates that aerodynamic noise generated by the flowing air could limit the magnitude of noise attenuation inside the duct achievable by means of linings. Mangiarotti\textsuperscript{39} in his study to investigate the basic properties of acoustic linings for reduction of fan noise in ducts found that the noise attenuated by the linings varied with the velocity of the air flowing along the duct. Correction factors for normalising the measured attenuation were developed (not reported), to account for the change in acoustic impedance of linings (resulting from change in particle velocity normal to the lining surface) due to the increased air flow velocity and sound pressure level. In a study using resin bonded fibreglass lining he found a substantial masking of the predicted lining attenuation, by the pressure level actually measured at the wall. The observed sound pressure level of the aerodynamic noise generated in the duct was found close to the level expected owing to the attenuation due to the lining.
Whether the air flow velocity or the turbulence generated noise is the limiting factor will depend to some extent on the geometric configuration of the duct; since substantial bend or change in section can result in excessive and undesired distortions of the velocity profile and associated levels of aerodynamic turbulence intensity.

The background noise level and reverberation characteristics of the wind tunnel put a limitation on making meaningful freefield noise measurements unless they are properly accounted for. Corrections for sound reflections from the wind tunnel walls can be derived from noise measurements of a point source in the free field and in the tunnel. Such calibration procedures carried out on Ames 40' x 80' wind tunnel by Hickey and Soderman have yielded wind tunnel noise evaluation within 4 dB of actual flight data except at the octave band 600-1200 Hz.

2.3 **Study of Microphone Response in a Flow Field**

A microphone placed in an airflow generates an output voltage that is dependent upon the magnitude of fluctuating pressure caused by turbulence. The output signal corresponds to the incident fluctuating force which is composed of the sound pressure and the pressure fluctuations of turbulence.

Nakamura investigated the relation between different physical properties of a microphone in an air stream and the sound pressure and pressure fluctuations caused by turbulent flow. The theoretical formula for the
turbulence fluctuated pressure is deduced, considering small variations of flow velocity in a quasi stationary flow tube under a low magnitude condition for percentage of turbulence (see Appendix 3). Two types of probe microphones were used to measure the response to pure turbulence field and the results compared with \( \rho v_0 \delta v_n \) measurements. It was reported that one microphone produced an output level in good agreement with the theoretical values. Another probe microphone which had four tiny holes located on the side wall of the tube produced an output level 24 dB below the theoretical value. A theoretical expression of the microphone output level in the airflow is obtained by assuming random incidence of pressure fluctuations on the microphone diaphragm by an analogy with sound waves.

Frequency characteristics of various microphone outputs, measured with flow velocity as a parameter indicated that while the output of probe microphone - I agreed with \( \rho v_0 \delta v_n \) for the range up to 1000 Hz, the output levels of 1” and \( \frac{1}{8} \)” diameter microphones without a grid deviate from \( \rho v_0 \delta v_n \) in the frequency range \( > 500 \) Hz(at 500 Hz deviation was reported as 5 dB for \( \frac{1}{8} \)” and 11 dB for 1” microphone; and increasing at higher frequency). The frequency at which the deviation starts \( "fc" \), is decreased as the diameter of microphone is increased and the mean airflow velocity is decreased.

Investigations were made by Nakamura 40 & 41
to find a physical concept for evaluating the pressure field of sound that exists in an airflow by means of a probe microphone. In order to provide a sound pressure in the airflow, sound of a known pressure level was radiated into a duct from an external sound source. The output level of the microphone was measured for various differences between the S.P.L. produced by the external source of sound and the pressure fluctuation level of turbulence in the air flow. If the sound pressure existing in the flow is negligible, compared with the pressure fluctuations of turbulence, it was reported that the output of the microphone in airflow is determined by turbulence fluctuated pressure, which is proportional to the product of flow velocity and infinitesimal fluctuation of velocity. On the other hand if the sound pressure is not negligible the output of the microphone shows the level corresponding to a superposition of output produced by the sound pressure with the output produced by the turbulent pressure fluctuations. Also it was reported that the $jv_0Sv_n$ component of turbulence decreases almost linearly as the distance from the source of turbulence and at sufficient downstream distances ($L = 90$ cm or more) the microphone responds mainly to sound pressure fluctuations beyond a frequency of 160 Hz.

The author tried different types of probe microphones having different response to turbulence fluctuated pressure $jv_0Sv_n$, and found that the lower limit for measurement of S.P.L. by a microphone in an air flow can be lowered by
decreasing the microphone output produced by the pressure fluctuation of turbulence. Incidentally one of his probes (design not fully disclosed in paper) had a very selective response to turbulence and very good correlation was found between the microphone output while responding to a pure turbulence field and the \( \rho v_0 \delta v_n \) component expressed in decibel reference \( 2 \times 10^{-5} \text{N/m}^2 \). Thus a new parameter (\( \Delta \)) had been defined as difference between the output level produced by pressure fluctuations of turbulence and the level estimated by \( \rho v_0 \delta v_n \), and it was found nearly independent of wind flow velocity.

Theoretical and experimental investigations of microphone probes in turbulent flow, conducted by Neise\(^{37}\) indicate that the turbulence noise signal can be reduced considerably (and hence signal to noise ratio could be improved) by means of a cylindrical tube with an axial slit, which is covered with the cloth. The signal-noise ratio increases with both frequency and tube length; and becomes smaller for higher flow velocities. The reasoning for the high level of turbulence rejection by this set up is as follows:

A fluctuating pressure field outside the tube excites pressure disturbances along the wall inside the tube. From there the pressure is propagating as a sound wave to the microphone as well as to the top. All sound waves at the top are totally absorbed. The pressure at the microphone is determined only by the waves directly propagating from the tube wall to the microphone. When summing them up one
has to consider their phase shifts due to different travelling times from the points of excitation at the wall of the microphone. If there is an external plane sound wave travelling in the positive 'x' direction, the pressure disturbances excited along the inner wall are different in phase due to the wave propagation outside. However at the microphone the phase difference is compensated by the different travelling times, because the propagation velocities inside and outside are equal. In case of a turbulent pressure field outside the tube, the pressure disturbances excited at the inner wall are likewise different in phase. But now the phase difference cannot be compensated by the travelling times because the turbulent field outside is converted with a speed of the order of the flow velocity and all waves interfere with each other and the pressure measured at the microphone is much smaller. The smaller the wavelength or higher the frequency; this pressure compensation effect was found to be stronger. Using this method Neise\textsuperscript{37} and Wang\textsuperscript{36} both could obtain turbulence noise rejection from 12 dB at 100 Hz to 24 dB at 1 kHz.

In another study the influence of flow velocity, turbulence level, turbulence scale size and nose cone diameter; on overall microphone wind noise levels and spectrums was investigated by L. J. Oswald\textsuperscript{21}. For the range of the average turbulent scale sizes investigated in this study ($\lambda_a = 20$ to 145 mm); no effects on the overall A-weighted noise level was found for the three nose cone sizes.
investigated. An empirical relation has been reported for A-weighted wind noise levels of nose cone protected microphones as follows:

$$SPL_{A(wind)} = 73.0 - 18 \log_{10} \frac{D}{25.4} + 24 \log_{10} \frac{T.I.}{0.015} + 58 \log_{10} \frac{v}{20.1}$$

where $D$ is the nose cone diameter in millimeters, T.I. is the turbulence intensity, and $v$ is the flow velocity in meters per second. The accuracy of this formula was reported to be within ± 3 dBA within the range of investigation ($v = 30$ m/s).

In an investigation of foam windscreen by Bloomquist regarding wind generated noise rejection, a maximum noise reduction of 20 dB has been reported for a 18 cm diameter 800 pores/m spherical windscreen with a wind speed of 40 km/hr. The insertion losses under random incidence conditions were measured in a large reverberation chamber (425 m$^2$); excited by broad band pink noise and were found to be negligible.

2.4 Acoustical Investigations Related to Present Study

In recent years there has been a growing awareness that deterioration of hearing may result from continuous exposure to noise that varies in space and in time. In order to analyse the sound field around a moving person and to record changes in sound level, duration or temporal pattern: a subminiature wide band electret microphone coupled to a casette tape recorder was used by Brammer in a study on operators of snowmobiles. This kind of
information is not provided by conventional dosimeters. Also the changes in level and consequent exposure resulting from the use of extra aural hearing protectors can be determined in service. Moreover locating the microphone in the cavum of the concha permits reasonable assessment of the noise without the problems associated with aerodynamic turbulence exciting microphone diaphragm.

In a study by A. J. Brammer, on comparison of noise field at ear and near the head on snowmobile riders it was noticed that perturbations to the sound field in the vicinity of operators of recreational vehicles may result from the presence of reflecting surfaces.

Such noise measurements carried out simultaneously at two locations in a semi-anechoic chamber with riders and snowmobile on a chasis dynamometer indicate that levels observed at the cavum of the concha are significantly greater than those 3" from the head at frequencies between 1.25 KHz and 6.3 kHz. These frequencies correspond closely to those at which significant pressure gain can be attributed to the concha and pinna flange. However at lower frequencies especially around 400 Hz, it was reported that the levels observed near the head, significantly exceed those within the ear. This difference is possible due to wave interference arising from the position of body relative to the ear. It was observed that while a difference of more than 5 dB exists between levels at the cavum of concha and 3" away from the head both at high and low frequencies, the difference between
the overall A-weighted S.P.L. is just 2 dBA; the level inside the ear being higher.

A comparison of sound levels within the ear and 50 feet from snowmobiles operating at full trottle on snow reveal differences in level from 21 to 30 dB with significant variations from one snowmobile to another. This reflects the complicated relationship between pressure amplitudes and distance around a vehicle containing several important sources of noise.

2.5 Noise Experienced by Riders of O.R.V.

It is inappropriate to consider the exposure resulting from one recreational activity in isolation, since an individual may engage in a variety of noisy activities. Hence it is difficult to estimate the consequences of exposures that vary in intensity, duration, and occur infrequently. A more satisfactory approach to this problem would be to treat the combined effect of noise exposure during recreation. For this reason we should consider the sound levels experienced by operators under various conditions, and compare those to a level considered acceptable for continuous exposure. An energy equivalent A-weighted sound level \((L_{eq})\) of 75 dB has been proposed (by E.P.A. wide Rep. 550/9-74-004)\(^{15}\), as the limit for continuous exposure to sources of environmental noise. A desirable effect of this limit is that no significant change in hearing threshold would result if these limits are complied with. The results of above study on snowmobile indicate a non-linear
relationship between noise output and vehicle speed and it varies considerably between machines. Also no evidence of air turbulence effect around the head or microphone was observed in those snowmobile runs. A significant contribution from either of these effects would have caused the level at ear for different vehicles to tend towards a common value, as the speed increased.

In a study on variation of sound pressure within the concha; Shaw has found that for all angles of incidence, the pressure difference between the eardrum and the concha is substantially independent of the position of the probe within the cavum of the concha at frequencies below 6 kHz. In this frequency range departures from a common value were less than 1 dB except when the probe is located at the entrance to the ear canal.

In order to compare noise data recorded at concha with existing standards for hearing conservation, which are stated in terms of sound pressures that would be produced at the centre head position in a diffused field; it has to be adjusted for pressure transformation from concha to diffused field. This is done electronically by using a graphic spectrum equaliser.

An interesting study on the baffle effects of the human body and its effect towards changing the frequency response of microphone has been reported by W. Hanson. The most significant factors reported are the source frequency, the shape and direction of sound waves, size and shape of
the person, the position of the microphone on the person, posture and the type of clothes worn. It has been shown that the effective response of a hearing aid is changed approximately 10 dB, when it is worn by a person facing a source of sound in nearly free field conditions. In general lower frequencies are enhanced by about 5 decibels and higher frequencies (>1 kHz) reduced by up to 5 dB. The scatter of data is so wide that even under the relatively simple conditions of a normally incident plane sound wave, it is difficult to adopt a single standard correction curve. The study of interaural pressure difference indicates that the most significant changes occur during the first 30° of head rotation. This is consistent with the commonly known fact that the optimum directional perceptual capability in humans occurs near zero degree orientation.

In another study on noise attenuation properties of motorcycle helmets, R. Harrison\textsuperscript{19} found that all helmets tested provided insignificant hearing protection at speeds below 45 m.p.h. and increasing hearing protection at higher speeds amounting to about 18 dB reduction over no helmet condition at 70 m.p.h. The typical average sound pressure level measured at riders' ear 55 m.p.h. was found to be 120 dBA without helmet and 108 dBA with standard helmet and bubble visor with proper fit.
3.1 General

A part of the wind tunnel was already in existence and was used in a study of internal flow in axial flow turbo machinery by previous investigators. The selection of fan, diffuser, honeycomb and filters etc. had been made so as to allow this tunnel to operate within a range $1.5 \times 10^5 < R' < 5 \times 10^5$. Since the most important design consideration for flow visualisation was streamlining the flow, the acoustical properties of the wind tunnel were not given sufficient importance. So the existing tunnel was modified to suit our aerodynamic noise investigations, which primarily involved a reduction of inherent noise.

It was decided to first measure the S.P.L's at the end of the convergent section of the existing setup. Overall dBA levels and octave band pressure levels were measured at the termination. The results are shown in figure 1. The A-weighted levels were found to be 92 dBA. Since the total wind generated noise within the desired velocity range was expected to be somewhere between 70 to 100 dBA, this tunnel background noise level was expected to interfere with noise measurements and hence an attempt was made to reduce it.
The head loss calculations for the expansion section filters, honeycomb and contraction section have been shown in reference 53. The total head loss was estimated to be 1.85" H$_2$O. No head loss calculations were performed for the acoustic plenum, convergent section and test section, as the head loss coefficients could not be evaluated with reasonable accuracy for those acoustically lined surfaces.

Based on a volume flow rate of 20,000 cfm and a required flow speed of 90 F.P.S. at the test section, a rectangular test section, measuring 28" across and 19" vertically was selected. The flow rate could be varied by the intake damper control unit. Tunnel walls were lined with 2" thick acoustical insulation and an intake plenum chamber helped to dampen suction noise. A 90 degree bend was given to the flow so as to maximise noise attenuation although at the expense of increased turbulence. Due to the space and cost limitations it was decided to have the test section discharge directly into the open space; and no divergent section with anechoic termination was provided to reduce head loss and possible standing wave formation.

3.2 Construction of Wind Tunnel and Test Section

Previous investigators have determined the optimum design angle for expansion to be in the neighbourhood of 5°. Smaller angles would increase losses due to friction, while too high a diffusion angle could produce excessive boundary layer buildup and eventual flow separation. In this case since the inlet section was not square, different
diffusion angles resulted for the sides and top and bottom. To economise space, a diffuser length of 8 feet was chosen, resulting into diffusion angles of $10^\circ$ for sides and $6.5^\circ$ for top and the bottom.

The expansion section has been connected via a flexi-connector to the fan to reduce any structural vibrations propagating down the wind tunnel. At the outlet end of the expansion section, a gauze unit has been installed to act as a final filter as well as to initially smoothe the flow of air.

Downstream the filter there is a short length, containing a honeycomb unit and a bank of screens to act as a settling chamber. The object of installing the honeycomb was to remove any swirl and eddies from the air flow.

Placed next to the screens was a contraction section having a contraction ratio of 0.33 and a head loss of 0.02" WG. This contraction section terminates into a straight coupler having a rectangular section. Upto this point the wind tunnel was already in existance and as mentioned before had been used in hydrodynamic flow studies. An initial study of flow and noise field at this section revealed that although the flow was uniform over most of the central area of the section, the noise levels were too high. Therefore it was decided to provide acoustic treatment to the inside surface of the coupler. The material chosen was 1.5 inch thick Fiberglass duct board.
Coupled to this was the acoustic chamber with outside and inside dimensions shown in Figure 3. It was constructed by the previous investigators for exhaust shell noise study.

It was decided to give a 90° bend to the flow direction at this point in order to produce maximum attenuation to the directly radiated sound pressure from the fan. This resulted in additional turbulence in flow, and hence higher amount of aerodynamic noise in flow.

Because of the relatively low Reynolds numbers ($R'_c = 3.5 \times 10^5$) at which the tunnel was to be operated, the use of corner turning vanes was ruled out although it would have resulted in increased corner efficiency both aerodynamically and on the energy basis. Based on a volume flow of 20,000 CFM and area of test section 19" x 28" a contraction section was designed with top and bottom inclinations of 5°30' and 4°36' respectively and side flare 2°20' either side. These values were picked to give suitable space economy.

The dimensions of the contraction section were as shown in Figure 4. It was constructed out of 3/8" plywood mounted on a 2 x 2 wood frame and lined with 2 1/2" R-7 grade fibreglass wool used in sound absorption. It was glued to the plywood panels with panelling cement and covered with chicken wire to keep it in place.

Attached to it was the working section whose shape was chosen to be rectangular so as to provide ease in rigging and mounting of the model and also to simplify the construction of entry door. The closed throat working section used,
resulted in a uniform and steady flow field across the test section and a reasonably low intensity of turbulence, 1.68 % at 84 F.P.S.

A gradual taper along the length of the working sections, to allow for the growth of the boundary layer and hence for the uniform velocity along the length, was found unnecessary, as the test model was small and slight variations in velocity could be tolerated.

The working section length is usually not less than 3x diameter. Therefore a slightly longer test section was made; (98" long with the internal dimensions of 28" wide and 19" high); so as to generate wind speeds upto 90 F.P.S. at the working section. A detailed drawing of the wind tunnel is shown in fig.2.
Motor Rating
horse power = 50
60 cycles 3 phase input
Rated r.p.m. = 1800
Rated current = 46 amp.

Blower Make
Manufacturer: Canadian Blower and Forge Co. Ltd.
Type: Centrifugal blower, type BL-660
Delivery Pressure: 7.5" SPWG.
Velocity: 3200 FPM.
Outlet Area: 6.26 Ft.²

Contraction Ratio
1.15

3.4 Design Evaluation

The important contributors to the tunnel overall background noise were thought to be the fan noise and aerodynamically generated noise. In order to reduce fan noise some fan noise samples were taken and analysed for its frequency composition. A B & K 4134 pressure probe microphone was used and samples taken outside blower housing near the hole for drive shaft. The frequency spectrum was as shown in the Figure 5. The spectrum shows the fundamental at blade passing frequency (390 Hz) and harmonics of it. Other harmonies from different wind tunnel sources were comparatively less prominent.

The microphone was then placed outside the flow
near the flexible coupling (connecting blower to the diffuser), in order to remove velocity pressure fluctuations effecting the microphone output. The frequency analysis of the microphone output was as shown in Figure 6. It was observed that the spectrum was essentially the same although there had been an increase in pressure amplitudes. It was observed that the flexible coupling which was 14" long, when inflated was vibrating excessively and could be the reason for the amplitude increases. To check it, a B & K 4333 accelerometer was placed on top of the coupling to monitor acceleration levels while running the fan at maximum rated r.p.m. The typical frequency spectrum obtained is shown in Figure 7. This is a narrow band analysis in the frequency range 0-2 kHz with low frequency cut off at 22.5 Hz. The spectrum consists of discrete frequency components and harmonics with amplitudes dropping off in the higher frequency range, beyond 1 kHz. It was then decided to reinforce this section by lining the coupling with 3/8" plywood and leaving 1" space either side so as to maintain flexibility, and to avoid any direct transmission of fan vibrations to the diffuser. Vibration levels were again measured at the same point on coupling and the frequency analysis is as shown in Figure 8. A significant reduction in acceleration amplitudes is observed throughout the frequency range although a prominent spike is observed at 60 Hz. No further attempts were made to reduce these low frequency amplitudes since the low frequency amplitudes would be highly attenuated when A-weighted. The 60 Hz spike corresponds to the mains frequency.
In order to study the change in blower noise as a result of closing the inlet damper vanes for flow regulation, noise measurements were made inside the blower housing at two different speeds. The measurements were taken with a pressure microphone fitted with a probe tube, which was inserted into the housing through the hole for the drive shaft, and the frequency spectrum was found to be as shown in Figure 5A. It is observed that essentially there is no significant change in the spectrum with the decrease in flow; however, there is a slight increase in noise amplitudes. This is expected to be due to the inlet noise which increases as the restriction to intake flow is increased by damper closing as shown by noise measurements made in inlet plenum box, as shown in Figure 24.

Next, the acceleration levels were measured at different points on the blower and drive train and a typical frequency spectrum so obtained is shown in Figure 9 and Figure 10. It shows that blower housing vibrations produce a fairly broad band frequency spectrum with amplitudes tapering off at higher frequency end, which is similar to the spectrum obtained on top of the flexible coupling.

The vibration levels at the bearing-housing supports were found to be significant only in the frequency range from 5000 to 7000 Hz. Since these vibrations were not carried forward, no attempt was made to reduce them.

Acceleration levels on top of the diffuser are
shown in Figure 11. Here again it was found that low and high frequency amplitudes were fairly low while those of any significance existed in the frequency range 1-1.2 K. Attenuation of these vibration levels was not attempted, as stiffness control would not have helped since these panels were made out of 1" thick plyboard. However it was decided to provide rubber pads under the mountings so as to isolate any floor transmitted vibrations. At this point it was decided to complete the rest of the tunnel and finally measure vibration levels at test section, in order to see if any significant amplitudes appear at those frequencies; after being attenuated during the passage through the acoustically lined tunnel. They were found to be well attenuated as observed in spectrum in Figure 12.

The test section and the acoustic intake box were made out of 3/8" plywood and were braced with 2 x 2 wood sections to improve their stiffness. The vibration levels were then finally measured on them and are shown in Figures 12 and 13. Both the spectrums indicate low frequency amplitudes and they should be well attenuated when A-weighted during sound pressure measurements.

In order to evaluate the noise levels at the outlet from the existing portion of wind tunnel, measurements were made at the acoustic plenum box with its lid removed and with the intake damper fully closed. Figure 1 shows the overall A-weighted and octave band pressures at various positions as shown. An overall S.P.L. of 92 dBA was noted.
It indicated that at least 20 to 25 dBA reduction was necessary in the added portion of wind tunnel in order to have a reasonable range of wind noise measurements, free from background noise interference.

After construction the wind tunnel was run at the rated r.p.m. and full intake damper opening and the velocity field was probed at the test section with a pilot static tube and inclined manometer. The velocity distribution in the horizontal and vertical axis at the T.S. was found to be as shown in Figure 14. Since the velocity profile was fairly uniform at the centre of the test section, where the model was located, this construction was considered to be satisfactory. Finally Figure 14A shows the octave analysis and A-weighted S.P.L. at the test section before and after the modifications. An overall improvement of 20 dBA had been achieved as a result of the above manipulations.
CHAPTER IV

INSTRUMENTATION

4.0 General

Most of the instrumentation involved in the present study for measurements and data reduction was Brüel and Kjaer, Spectral Dynamics Corporation and D.I.S.A. makes, which fully meet the I.E.C. and A.N.S.I. requirements for precision and accuracy. Since these makes are well known for good accuracy and repeatability of results, only a brief description of their important features and the calibration procedure will be given here. However, certain non-standard units that were built and put together like the ear bug system for monitoring of temporal variations in noise levels at the ear, will be described in greater detail. The instrumentation systems used in various measurements are as shown in Figure 38A, 38B, 38C and 38H.

4.2 Ear-Bug Noise Monitoring Unit

The apparatus essentially consists of a miniature wide band electret film microphone, small enough to fit within the concha and coupled to a commercial cassette tape recorder through an impedance matching circuit. This produces a permanent record of pressure fluctuations at ear as a function of time. Changes in sound pressure level,
duration and temporal pattern may be obtained from this data to establish conformity with the existing hearing conservation criteria. The noise dosimeters working with fixed integrating limits, however do not provide this capability.

A sketch of the apparatus used is given in Figure 15. It consists of a Knowles Electronic Inc. BT-1785 series subminiature pressure transducer using polarised electret film. The overall dimensions of the microphone are 2.28 x 5.59 x 9.49 mm. It was mounted in a housing with three connections. The nominal supply voltage was 1.1-1.3 V.D.C., output impedance 6000 Ω, current drain 0.01 to 0.05 mA DC (max); and open circuit sensitivity of 60 dB below 1 volt r.m.s. per microbar (0.1 N/m²) r.m.s. pressure. It was connected through an impedance matching circuit to a modified 'Sony' cassette tape recorder model TC-55. The overall dimensions of the package were about 24 x 11 x 6 cm; and weighed approximately 2 kg.

The electret microphone responds linearly from 3 Hz to 2 kHz with open circuit sensitivity increasing by about 3 dB/octave beyond 2 K to a peak value of 49 dB below 1V r.m.s. per microbar (0.1 N/m²) at 5 kHz. (These values are not exact as data sheets for the particular microphone employed were not available from the manufacturer.)

The output feeds into an impedance matching circuit which produces a desired attenuation of the signal so as to obtain a linear dynamic range of 30 dB. at recorder input (defined when the transfer function is linear within ±1 dB.). The ear bug recorder input attenuator essentially consists
of a series and a shunt resistance connected as shown in Figure 16, to obtain different linear ranges in dynamic response as indicated in Figure 16. Thus depending on the expected range of measurements an attenuation circuit could be selected so as to have a linear dynamic response throughout the measuring range. The frequency response (90 Hz-10KHz.) of the tape recorder is modified to A-weighting and the internal gain control in the recording mode is disabled. Another modification is a 1.3 V D.C. voltage output made available at the input jack for supply for the ear bug microphone. The built-in microphone of the tape recorder is disconnected so as not to superimpose another sound field while recording.

With these modifications the free field frequency response of the earbug with different attenuators is as plotted in figure 17. Comparison of this response with the standard A-weighting curve shows that the ear bug produces relatively less attenuation at frequencies below 0.5 kHz and too high attenuation beyond 3.1 kHz. In order to compensate a B & K graphic spectrum equaliser #125 was used with variable gain control at selected centre frequencies (defined as 'preferred' 1/3 octave band centre frequencies by A.N.S.I.). The corrected (shaped) final output of the ear bug unit is plotted in Figure 18, against the standard A-weighting with A.N.S.I. type II tolerance limits (SI-4-1971).

Figure 19 shows the directional response of ear bug microphone at 1000 Hz for different incidence angle.
shows the directional response at different frequencies in terms of the Relative S.P.L. It can be inferred that up to about 3 kHz systematic errors due to orientation of microphone can be expected to be within ±1 dB as indicated by the close cluster of the points, at each frequency; beyond which the deviation increases to almost 3 dB at 5 kHz. Since we are measuring A-weighted broad band wind noise, with important frequencies below 1 kHz as seen in the spectrum; and also because of the fact that tunnel acoustic insulation produces an effective attenuation beyond 1 kHz, a directional response error of this magnitude from ear bug is not significant enough to effect the results.

The earbug system calibration was performed with B & K 4230 sound level calibrator; which is an oscillator generating a 1 kHz constant amplitude signal at 93.6 dB. It is recorded on the magnetic tape. Departures from this level may subsequently be taken to indicate that the batteries have discharged or a malfunction in the system. As the low noise magnetic tape cassettes used in this study possessed variations in sensitivity of less than ±1 dB; small errors in signal amplitudes can be detected in this way with the above accuracy.

4.3 Brüel and Kjaer Sound Level Calibrator Type 4230

The calibrator is based on a 1 kHz stabilized oscillator which drives a piezo electric bender, coupled to a membrane which produce a sound pressure of 94 dB in the coupler volume. A special adapter was designed to fit onto
the coupler volume to accommodate the ear bug microphone. When calibrating for pressure response measurements, no correction is required for calibrator output; however, when calibrating microphone for free field measurements a correction factor of -0.4 dB for 1" microphones and -0.2 dB for \( \frac{1}{2}\)" microphones has to be applied to the oscillator output.

4.4 **Brüel and Kjaer Graphic Spectrum Equaliser Model 125**

This equipment modifies the frequency response of an audio system to any desired shape. The input signal feeds an amplifier which drives twenty-five, one third octave filters. Each filter feeds a separate buffer amplifier which couples each filter to its own slide attenuator. An output amplifier sums the signal output from each attenuator and provides a low impedance driving source. The range of each attenuator is from +10 dB to -40 dB.

4.5 **Brüel and Kjaer Level Recorder Type 2307**

This instrument is capable of automatic recording of Average, Peak or R.M.S. level of A.C. components of signal with crest factors of up to 10 times \( V_{\text{rms}} \) and with an accuracy of \( \pm 0.5 \) dB, on preprinted charts with either time or frequency base. The paper drive and hence the 'x' coordinate can be remotely controlled by frequency analyser or a beat frequency oscillator through suitable drive units to plot spectrograms. Paper speed (0.3 mm/s) was selected. Writing speed was selected as 200 mm/sec, which corresponds to
"fast" response of R.M.S. detectors in the filter circuit. The stability criterion is based on matching the resolving power of level recorder with the dynamic range of the range-potentiometer in use.

4.6 **Brüel and Kjaer Beat Frequency Oscillator Type 1022**

This is a precision signal generator covering a range from 20 Hz to 20 kHz. It can be swept continuously through its frequency range by means of an external motor drive and can be synchronised with the level recorder. The frequency setting accuracy is 1 percent of full scale reading. The output voltage can be varied from 120 \( \mu \text{V} \) to 12 v in accurate 10 dB steps. The attenuators have an accuracy of 2 percent with an overall voltage inaccuracy of 1.5 percent over the frequency range from 20 Hz to 20 kHz. A feedback voltage from a regulating microphone to a variable potentiometer (compressor circuit) in the input stage of the regulating amplifier can be used to control the output power from the instrument. This feature is particularly useful when studying microphone response and doing equipment calibration under non-anechoic conditions, as prevalent in the laboratory, where systematic errors due to reflection effects may be reduced considerably.

4.7 **Brüel and Kjaer 2706 Power Amplifier**

The 2706 provides a 75 watt power output into a 3 \( \Omega \) load. It has a frequency range from 10 Hz to 20 kHz and a maximum voltage gain of 40 dB. Third Harmonic distortion...
is less than 0.5 percent at full capacity. Output signal clipping is indicated by a warning light. The power supply is 120 V.A.C.

4.8 **University Sound Model G.L.C. Weatherproof Hi-Fi Speaker**

This speaker has a L.C.F. (lower cut off frequency) of 85 Hz with a maximum sound pressure level of 110 dB at 1000 Hz, four feet on the axis. Maximum power is 30 watts with an eight ohm impedance.

4.9 **Brüel and Kjaer Generator Type 1405**

It is a highly stable random noise generator producing "white" noise up to 100 kHz. It contains a -3 dB/octave built in filter and a compressor circuit, both of which may be used independently. Signal to noise ratio is better than 90 dB.

4.10 **Brüel and Kjaer Frequency Analyser Type 2107**

It is an audio frequency analyser of constant percentage band width type. It has a narrow band width of 5 percent of tuned in centre frequency and has an analysis range from 20 Hz to 20 kHz. A built in mechanical device permits automatic tuning from an external motor (e.g. the B & K level recorder); to plot frequency vs. amplitude diagrams of input signal on frequency calibrated recording paper. It is supplied with an output switch, by means of which peak, R.M.S. or average value of the input signal can be selected.
4.11 Brüel and Kjaer Audio Frequency Spectrometer Type 2112

The audio frequency spectrometer is designed for analysing fluctuating voltage signals from transducer in the frequency range 22 Hz to 45 kHz. It consists of an input amplifier, a filter system of band pass filters and weighting networks, and an output amplifier. The filters may be selected electro-mechanically through a switching device like B & K level recorder and a continuous spectrogram can be recorded on preprinted frequency calibrated paper.

The indicating meter is equipped with three different rectifier circuits which enable the true R.M.S. value, the average absolute value, known as average value and half peak to peak value of the signal to be measured. The power supply contains the necessary rectifiers for operation of the amplifiers and also for operating B & K condenser microphones or vibration pick-up preamplifiers, whichever is used. The input impedance of spectrometer is 2.2 Mohm paralleled with 30 pF when the input switch is in 'Direct' mode. The frequency response of filter is flat within $\pm \frac{1}{2}$ dB over approximately $\frac{1}{2}$ octave in a 1/3 octave filter. At the band limits, i.e. 1/6 octave from centre frequency, the attenuation is approximately 3 dB while at $\pm 1/3$ octave from centre frequency the attenuation is 20 dB. Because of the effective bandwidth being greater than the true 1/3 octave band width by 9 percent maximum error introduced in measurements is within $\pm 0.4$ dB. The instrument stability is better than $\pm 0.3$ dB for a deviation of $\pm 10$ percent of power supply.
voltage. Signal to noise ratio is better than 60 dB, with range multiplier switch in position '0' dB.

4.12 **B&K Impulse Precision Sound Level Meter Type 2209**

This instrument fully meets the I.E.C. publication 179 requirements in full. It measures free field S.P.L. with accuracy of ±1 dB under specified reference conditions, during the normal use. The meter dynamic characteristic referred as "fast" is used to obtain a meter response to a signal of 200 milliseconds duration which is indicated within an accuracy of +0 to -2 dB, of the indication for a steady signal of the same frequency and amplitude. Meter damping is such that the over swing of the steady level produced by a suddenly applied signal is within +1.1 to +0.1 dB. The frequency response with 1" microphone type 4145 is linear from 4 Hz to 12 kHz within ±1 dB. Sensitivity is 50 Mv/N/m². The dynamic range is 15 to 140 dB at A-weighting. Input stage impedance is 1 GΩ in parallel with <1 pF.

4.13 **Measuring Amplifier - Brüel and Kjaer Type 2607**

The instrument meets the I.E.C. recommendation No. 179 and is capable of an extensive range of sound, vibration, and voltage measurements. It is a wide band measuring amplifier for linear as well as logarithmic operation, and includes true R.M.S. and peak rectifier circuits. The rectifier circuits contain time constants ranging from 0.1 to 300 seconds which may be directly or remotely selected to give averaging time for R.M.S.
measurements and decay times for peak measurements. A
display meter with interchangeable scales, on which the
range setting is automatically indicated facilitates the
direct calibration of 2607. Built in frequency weighting,
high and low pass filter networks and 50 mv R.M.S. calibra-
tion signal is also available. The instrument frequency
response is linear from 2 Hz to 200 kHz. Input stage
impedence is 900 kΩ// 50 pF. The gain of input amplifier,
adjustable to compensate for different transducer sensitivity
can be varied up to 14 dB by screwdriver operated potenti­
meters. A.C. output impedance is 50 Ω and the maximum output
is 50 v peak. The time constants corresponding to 'fast'
and 'slow' meter damping characteristic is in accordance with
I.E.C. and DIN recommendations.

4.14 Statistical Distribution Analyser - B&K Type 4420
This instrument when used in conjunction with level
recorder, can resolve measurement data (sound pressure levels)
into twelve class intervals and presents a numerical display
which helps in statistical analysis of signal and calculation
of equivalent continuous noise level (Leq). Individual
probabilities for each of the 12 channels may be calculated
and when added together must be 1.0 as the probability of
a certainty is 1.0.

4.15 S.E. Eight-Four Portable Tape Recorder
This is a four channel magnetic tape recorder which
incorporates a precision drive, capstan servo system to
control the tape speed. Three alternative tape speeds viz.
15, 3 and 1.5 i.p.s. are available. Frequency modulation (FM) and direct recording (D.R.) data electronics modules are available so that the data channels can be equipped to operate in the F.M. or D.R. recording modes. A voice module and a hand held microphone/speaker provide speech recording/playback facility. Speech is recorded on channel 1 and when voice record switch is operated, data input to channel 1 is interrupted. A combined d.c./peak a.c. voltmeter is used to indicate input and output voltages of the data channels.

Tape speed accuracy is better than 0.25 percent. Tape flutter at 15 i.p.s. tape speed, measured as per L.R.I.G. specification 106-69 is 0.35 percent peak to peak with a flutter bandwidth of 0.2 to 2500 Hz. Input stage impedance is 20 kΩ/20 pF. Output impedance is less than 10 kΩ. Temperature drift is ± 0.05 percent of full scale per degree C. Amplitude response is flat within ± 0.5 dB from 70 Hz to 60 kHz at 15 i.p.s. speed with an R.M.S. signal to noise ratio of 39 dB. Meter range is 1.5 v peak A.C. with a meter accuracy of ± 1dB for peak A.C. indication.

4.16 Brüel and Kjaer 1"-Condenser Microphone Type 4145
This microphone meets the A.N.S.I. requirements for type 'L' microphones for free field measurements. An important design feature for these microphones is that the line constant of the charging circuit is much longer than the period of the sound pressure variations. When sound pressure waves are incident upon the diaphragm, capacitance
changes and an E.M.F. is produced which is proportional to 
the sound pressure level within the dynamic range. The 
nominal open circuit sensitivity of the microphone is 50 mv/
N/m² i.e. -26 dB relative to 1V per Newton/m². The actual 
sensitivity with an F.E.T. preamplifier may be calculated 
from the open circuit sensitivity given on calibration chart, 
the voltage gain of cathode follower, its capacitance and 
the cartridge capacitance. The low frequency limit (-3 dB 
Point) is 1 Hz on frequency response curve which can be 
extended up to 0.1 Hz by sealing equalisation vent with a 
gasket. Frequency response is linear within 1 dB (at 0° 
incidence) up to 2 kHz under free field conditions. 
Polarisation voltage is 200 v.D.C. It has excellent 
sensitivity stability and at room temperature it is given 
as 0.2 dB per 1000 years. Random incidence corrector makes 
the microphone response omnidirectional; presenting a 
microphone sensitivity independent of both the angle of 
incidence and the frequency in the measuring range. Dynamic 
range (ref. 2 x 10⁻⁵ N/m²) is 144 dB upper limit to a lower 
limit depending upon the noise level of preamplifier. 
Ambient pressure effect (ref. 250 Hz) is 0.3 dB increase 
for 100 mm 'Hg' decrease.

4.17 B&K Half Inch Condenser Microphone #4134

It is a high stability precision condenser microphone 
for pressure measurements. Nominal sensitivity is 12.5 mv/
pascal at 250 Hz, -38 dB ref. 1 mv/pascal with 200 v. 
Polarisation voltage. It is designed for a linear pressure

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response up to 20 kHz ($\pm$ 2 dB). When used in conjunction with field effect transistor (F.E.T.) preamplifier B&K 2619 it gives a lower limiting frequency (L.L.F.) of 2 Hz (-3 dB point). At frequencies below 20 Hz the response of the microphone cartridge continues as a straight line until close to the lower frequency limit (-3 dB point) determined by pressure equalisation and preamplifier noise, and is between 1 to 3 Hz with 2619 preamplifier. Directivity errors are within 2.5 dB up to 5 kHz. The upper limit of dynamic range is set by the harmonic distortion and is about 160 dB for 3 percent total harmonic distortion. Dynamic range upper limit is 164 dB ref. 20$\mu$ Pascals (4% total harmonic distortion), and lower limit determined by Preamplifier noise. Influence of ambient pressure on response is -0.1 dB/100 mm 'Hg'.

4.18  Brüel and Kjaer Probe Microphone Kit UA 0040

Probe tubes are used in conjunction with pressure microphone 4134 to reach restricted cavities for acoustic pressure measurements. The performance (frequency response) of probe depends upon the length, width, acoustical impedance of microphone cartridge (equivalent volume of cartridge) and the volume between the microphone diaphragm and the end of the tube terminating this volume. The tube diameter is very small compared to the wavelength; but the length of tube is kept several times larger than the wavelength for a great portion of the audio frequency range. Resonance would appear at frequencies when tube length equals odd multiples of
quarter wavelength, with antinode occurring at the open end. By suitable damping a smooth frequency response may be obtained over the desired frequency range.

4.19 **B&K Piezoelectric Accelerometer 4333 With Voltage Preamplifier 2623**

It is an electromechanical transducer giving an electric output proportional to acceleration level, over the dynamic range of the instruments. The voltage sensitivity was 20 mv/g with a useful frequency range from 1 Hz to 10 kHz. This accelerometer is recommended for general purpose vibration measurements and weighs 13 grams. The voltage amplifier 2623 has fixed gain 0 dB ± 0.05 dB. The dynamic range extends from practically zero 'g' to about 9000 'g'. Since we are measuring fairly low acceleration levels (≠ 3 g) no appreciable zero drift was expected in accelerometer output due to residual charge. Power supply to the transducer is through the adapter ZR 0024 fitted to measuring amplifier - preamplifier input socket.

4.20 **B&K Accelerometer Calibrator Type 4291**

The accelerometer calibrator type 4291 is designed to give a calibration level of 1 'g' peak. This means that having set the calibration level correctly, the test accelerometer will be subject to a maximum acceleration of 1 'g' (9.806 m/s^2 or 32.14 ft/sec^2) at a frequency of 79.6 Hz. The power supply is 28 v D.C. from an external source. The accuracy of calibration is better than ± 2 percent.
4.21 Spectral Dynamics Corporation - Real Time Analyser Model SD 301c

This analyser provides 'ONLINE' spectrum analysis capability in audio frequency ranges; with input frequency ranges up to 50 kHz and a resolution bandwidth down to 0.03 Hz. It is highly flexible in operator-selected modes of operation. The output spectra is provided in either linear or log forms; fast enough for a flicker-free oscilloscope display or slow enough for an X-Y recorder. A memory capture mode allows a segment of input data to be stored for examination. The input signal is frequency analysed using 1000 synthesized filter locations that are tuned by a built-in sweep generator. The display outputs are proportional to the fourier components of the signal.

4.22 Spectral Dynamics Corporation - Octave Converter Model SD 305A

Octave converter in conjunction with SD 302A Ensemble Averager, increases the versatility of Real Time Analyser SD 301c, by providing capability for octave band spectrum analysis. The complete system provides real time narrow band as well as 1 and 1/3 octave contiguous band spectrum analysis by push button selection. The octave converter provides linear squared or logarithmic spectrum amplitude scaling and both linear and logarithmic frequency axis scaling. Outputs include analog functions for both oscilloscope display and electromechanical recorders and digital functions for computer interfacing. Twenty-one 1/3 octave filter outputs plus the overall linear level.
(which is displaced in the first segment) can be displayed simultaneously. A total of 57 contiguous band 1/3 octave filters can be viewed by selecting SD 301 analysis range.

4.23 Spectral Dynamics Corporation - Ensemble Averager-Model SD 309

It is designed specifically to work with SD 301 Real Time analyser. It accepts sequentially the linear spectrum outputs from R.T.A. and computes the average spectrum based on the number of ensembles selected and stores the peak value of each of the 500 tones of the spectrum. Front panel lights display the progress of linear averaging cycle by indicating when it is 25, 50 and 75 percent complete. The averaged data is then routed to linear or log amplifiers for display on either an oscilloscope or X-Y plotter. Ensemble is a sequence of spectrum outputs from R.T.A. One ensemble comprises 500 linear voltage steps; the value of each step is proportional to the sampled spectrum amplitude of a synthesized filter location in R.T.A. The above units have been shown in fig.38-1.

4.24 Spectral Dynamics Corporation Model 13116-2A X-Y Display

It is a large screen display oscilloscope. The spectrum is displayed on a 8 inch (vertical) by 10 inch (horizontal) display C.R.T.; an 8 inch by 10 inch graticule over the scope face is divided into 1 inch squares with subdivisions of 0.2 inch along the major axes. All input signals are accepted by B.N.C. type connectors located on
the rear of the chasis.

4.25 **Hewlett Packard Model 7045A X-Y Recorder**

It produces a cartesian coordinate graph showing the relationship between the two variables. The input terminals (Hi and Lo) are supplied with varying D.C. signals. These signals should vary at a rate within the response capabilities of the instruments and have amplitudes within their scale ranges or an erroneous recording may result. If excessive noise is present on the input signal (thereby resulting in recorder response becoming oscillatory) an external filter may be needed.

4.26 **Brüel and Kjaer Noise Dosimeter Type 4424 & 4425**

It is a self contained instrument for the automatic assessment of personal noise exposure according to ISO R 1999 (4424) or OSHA (4425). It also fulfils the relevant portions of I.E.C. 123 and ANSI SI.4-1971 Type S2A sound level meter standards. Readout of the noise exposure is by four digit L.E.D. display; 100 percent corresponding to the maximum allowed exposure of 90 dB(A) for 8 hours. It also indicates crossing of 115 dB(A) slow level as required by O.S.H.A. Sound detection is by a robust half inch condenser microphone. Simple calibration is performed using accelerated mode which (counting 115 times faster for 4424) may also be used for short duration measurements. The two versions are different only in their degree of amplitude weighting.
4.27 **D.I.S.A. Constant Temperature Anemometer Model 55M10 and Hot Wire Probe 55P11**

The anemometer is used to make an independent measurement of fluctuating velocity component, in a turbulent flow. The details of the instrument and its calibration curves have been reported in detail in Appendix 1A.

4.28 **Tandberg Tape Recorder.**

This is an audio frequency FM Tape recorder. It has a separate voice channel for simultaneous recording of voice. Its frequency response is as shown in fig. 69.
CHAPTER V
ACCRUACY OF MEASUREMENTS

In the present study the basic measurements were made for velocity and pressure. In an experimental investigation inherent errors are always present. These may be attributed to the fixed errors of instruments and the systematic errors in measurement. The latter source of uncertainty may be taken care of by the calibration of instrument with a primary instrument and fitting a least square curve. Other errors like response time, signal clipping, tube pinching etc. can be taken care of by following proper instrument procedure and operating within the dynamic range of the instruments.

5.1 Accuracy of Manometer

A Lambrecht inclined manometer filled with coloured alcohol (SG=0.8) was used to obtain the difference between stream pressure and stagnation pressure. The manometer was graduated in millimeters, had a total measuring range of 200mm, and was normally used with 1:2 inclination. Hence the differential head was measured with an accuracy of 0.015" H$_2$O; and the accuracy could be further improved to 0.006" H$_2$O by raising the inclination.
Accuracy of Pressure Measurement and Data Reduction

Instrumentation

Pressure measurements were made with B&K condenser microphones. Suitable care was taken to operate all transducers, recorders and analysis equipment within the dynamic range, defined as the instrument range where the transfer function does not deviate from linearity by more than \( \pm 0.5 \) dB.

5.2 Error Analysis for Velocity Measurements

Consider a uniform flow at low mach number with a pilot static probe for velocity determination. A pre-experiment estimate of the uncertainty to be expected in velocity measurements can be given as follows. The governing equation of an incompressible flow is

\[
v = \left[ \frac{2g_o \rho (p_o - p_s)}{P Q} \right]^{1/2}
\]

where \( \nu \) is the local stream velocity, \( \rho \) the local density; \( p_o \) is local stagnation pressure; \( p_s \) the local stream pressure and \( g_o \) is the proportionality constant in Newton's Law.

The pitot static tube indicates \( (p_o - p_s) \); assuming air as a perfect gas i.e. \( \rho_{\text{air}} = \frac{p_s}{RT} \); \( p_s \) may be obtained by pitot static tube, and the stream temperature is measured with a thermometer. To evaluate the error the initial flow condition may be defined as -

\[
v_{\text{max}} = 90 \text{ FPS}, \quad p_s = 14.7 \text{ psia and } T_s = 532^\circ\text{R}.
\]

Since \( p_s / R T_s = \rho \) (From the perfect gas law.) and 27.7 in. H\(_2\)O = 1 P.S.I.A.

Hence From equation I.

\[
v = \left[ \frac{2g_o R T_s (p_o - p_s)}{p_s} \right]^{1/2}
\]

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The resulting uncertainty \( \Delta v \) in velocity measurements is given as:

\[
\Delta v = \frac{\partial v}{\partial (p_o - p_s)} \Delta (p_o - p_s) + \frac{\partial v}{\partial T_s} \Delta T_s + \frac{\partial v}{\partial p_s} \Delta p_s.
\]

or:

\[
\Delta v = \sqrt{\left( \frac{g_o R}{\nu} \right)^2 \left[ \frac{T_s}{p_s} \Delta (p_o - p_s)^2 + \left( \frac{p_o - p_s}{p_s} \Delta T_s \right)^2 + \left( \frac{T_s}{p_s} \Delta p_s \right)^2 \right]}^{1/2}.
\]

5.3 Pitot tube uncertainty:

For the present flow conditions; for \( p_o - p_s \) = 2" water; assuming 20:1 odds for uncertainty statements, and no fixed error in calibrator while allowing for an uncertainty of \( \pm 0.5\% \) of \( p_o - p_s \) in calibrator, we have:

\[
\Delta \text{(Calibrator reading)} = \pm \frac{0.5}{100} \times 2 = 0.01 \text{ " water.}
\]

This would be the uncertainty on the mean fixed error at \( \delta_p = 2 \) inch = \( p_o - p_s \).

For the present work the pitot static tube was not calibrated with an independent measuring instrument; but based on calibration data of similar pitot tubes we may assume an uncertainty in readings as \( \pm 0.125 \) in. water. Hence overall uncertainty for the mean fixed error:

\[
\Delta W_p = \sqrt{\Delta W_{\text{calibrator}}^2 + \Delta W_{\text{calibration}}^2}.
\]

\[
\Delta W_p = \pm 0.01^2 + 0.125^2 = \pm 0.125 \text{ in. water}
\]

5.4 Manometer accuracy:

The most serious error in this regard would have been due to the capillary action, and may be assumed as \( \pm 0.1 \) in. water. Since we used 1:2 inclination the inclined manometer; the maximum reading error was \( \pm 0.02 \) in. water. Thus total manometer uncertainty reduces to:

\[
\Delta W_m = \pm 0.12 \text{ in. water.}
\]
This is the instrument uncertainty associated with the indication of the quantity \((p_o - p_s)\). For the absolute value of the stream pressure \("p_s\) we read the barometer. Assuming it was corrected for the elevation above sea level and mercury temperature:

\[\Delta W = \pm 0.01 \text{ in. (Hg.)} = 0.01 \times 13.6 = \pm 0.136 \text{ in. (water.)}\]

(Barometer)

5.5. Stream temperature uncertainty:

The thermometer used for indicating temperature had an uncertainty given by its least count, and was found as \(\pm 0.5 \, ^\circ\text{F}\). The true stream temperature would be different than the indicated temperature, depending upon thermometer recovery factor \("R_f\); stream velocity,"\(v\); specific heat of air at a constant pressure,\("c_p\); and heat transfer. Since air was moved at room temperature \(72^\circ\text{F}\), the last two effects could be ignored and \(T_i\) could be given as:

\[T_i = T_s + R_f \frac{v^2}{2g_o J c_p}\]

The difference is

\[(T_i - T_s) = 0.65 \times 90^2 / 2 \times 32.2 \times 778 \times 0.24 = 0.43 \, ^\circ\text{F}.\]

\[= \text{ The fixed reading error at 90 FPS.}\]

where \(T_i\) = Indicated temperature

\(T_s\) = True stream temperature; and

\(R_f = 0.65\) (assumed.)

This value actually fluctuates between 0.5-0.8 i.e. an uncertainty of \(\pm 0.15\). Assuming we are confident in our stream velocity guess to 10% of the true value, i.e. \(\pm 9\) FES. the uncertainty on the above fixed reading error could be given as:

\[\Delta(T_i - T_s) = \frac{\partial(T_i - T_s)}{\partial R_f} \Delta R_f + \frac{\partial(T_i - T_s)}{\partial v} \Delta v + \frac{\partial(T_i - T_s)}{\partial c_p} \Delta c_p\]

Neglecting \(\Delta c_p\) (which is \(\approx 0\))

\[\Delta^2(T_i - T_s) = \left[\frac{\partial(T_i - T_s)}{\partial R_f} \Delta R_f\right]^2 + \left[\frac{\partial(T_i - T_s)}{\partial v} \Delta v\right]^2\]

\[= \left[\frac{v^2}{2g_o J c_p} \Delta R_f\right]^2 + \left[\frac{v \cdot R_f}{g_o J c_p} \Delta v\right]^2\]

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\[ \Delta (T_1 - T_s) = \pm 0.02 \text{ } ^\circ \text{F}. \]

Therefore overall uncertainty in stream temperature is:

\[ \Delta^2_{T_s} = \left| \Delta (\text{fixed error}) \right|^2 + \left| \Delta (\text{reading error}) \right|^2 \]

\[ \Delta_{T_s} = \left[ (0.002)^2 + (0.5)^2 \right]^{1/2} = \pm 0.5 ^\circ \text{F}. \]

5.6. Overall resulting uncertainty in indicated measurements:

I. \( (p_o - p_s) \):

\[ \Delta p_o - p_s = \left[ \Delta^2 \text{pitot tube calibration} + \Delta^2 \text{indicator manometer} \right]^{1/2} \]

\[ \Delta p_o - p_s = \left[ (0.125)^2 + (0.12)^2 \right]^{1/2} = \pm 0.173 \text{ in. water.} \]

II. \( (p_s) \):

\[ \Delta p_s = \left[ \Delta^2 \text{pitot tube calibration} + \Delta^2 \text{manometer} + \Delta^2 \text{barometer} \right]^{1/2} \]

\[ \Delta p_s = \left[ (0.125)^2 + (0.12)^2 + (0.136)^2 \right]^{1/2} = \pm 0.22 \text{ in. water.} \]

Substituting these uncertainty values in equation 2,

\[ \Delta V = \frac{32.2 \times 53.35 \times \left( \frac{532 \times 0.173}{14.7 \times 27.7} \right)^2 + \left( \frac{2 \times 0.5}{27.7 \times 14.7} \right)^2 + \left( \frac{536 \times 0.22}{27.7^2 \times 14.7^2} \right)^2}{90} \]^{1/2} \]

\[ \Delta V = \pm 4.34 \text{ EES.} \]

5.7 Turbulence fluctuated pressure- error analysis:

The turbulence fluctuated pressure \( (P_t) \) is given as:

\[ P_t = \frac{\rho v_o \delta v}{g_o \times 144} \times 6.8947 \times 10^3 \text{ pascals} \] \hspace{1cm} (3A) \]

Where \( v_o \) is the stream velocity.
\[ \Delta P_t = \left( \frac{\partial P_t}{\partial \rho} \cdot \Delta \rho \right) + \left( \frac{\partial P_t}{\partial v} \cdot \Delta v \right) + \left( \frac{\partial P_t}{\partial v_n} \cdot \Delta v_n \right) \]

\[ = \left( v \cdot \delta v_n \Delta \rho \right) + \left( \rho \cdot \delta v_n \Delta v \right) + \left( \rho \cdot v \cdot \delta v_n \Delta v_n \right) \cdot \left( \frac{6.894 \times 10^3}{\varepsilon_0 \cdot 144} \right) \]  \(---(3)\)

assuming air as a perfect gas:

\[ \rho_{air} = \frac{p_s}{R \times T_s} \quad \text{where } \text{"s" is for stream functions.} \]

\[ \Delta \rho = \left[ \frac{\partial \rho}{\partial p_s} \right] \cdot \Delta p_s + \left[ \frac{\partial \rho}{\partial T_s} \right] \cdot \Delta T_s \]

\[ = \frac{\Delta p}{R \times T_s} \cdot \frac{p_s}{R \times T_s} \cdot \Delta T_s \]

\[ \Delta p = \frac{0.05}{53.3 \times 532} + \frac{14.7 \times 0.5 \times 27.7}{53.3 \times 532} = \pm 0.00001 \text{ lb/ft} \cdot 3 \]

\(V_{d.c.}\) was measured on D.I.S.A. digital milivoltmeter, with an uncertainty in measurements \(\Delta V_{d.c.}\) of 0.001 V; which is the least count of the instrument. The fluctuating component of velocity was measured on a B&K R.M.S. Voltmeter (Measuring amplifier model 2607); which had an accuracy of \(0.2 \times 10^{-6} \text{ V}_{\text{r.m.s.}}\). Neglecting any fixed error present in these instruments the absolute limits on the overall error of turbulence fluctuated pressure \(\Delta P_t\) may be given as follows:

from equation (3)

\[ \Delta P_t = 6.8947 \times 10^3 \times \left( 90 \times 1.896 \times 10^{-4} + 0.0746 \times 1.896 \times 10^{-3} + 0.0746 \times \frac{32.2}{144} \right) \]

\[ \Delta P_t = \pm 0.02558 \text{ Pa.} \]

If we now compute from equation (3A) the value of turbulence fluctuated pressure \(P_t\) at 90 FPS. flow velocity; we get;

\[ P_t = \frac{0.0746 \times 90 \times 1.896 \times 6.894 \times 10^3}{144 \times 32.2} = 18.92 \text{ Pa.} \]

where \(\delta v_n = 0.08 \times 90 / 3.78 = 1.896 \text{ fps.} \)

\(90 \text{ F.P.S.}\)

\(\rho = \frac{p}{R \times T} = 14.7 \times \frac{144}{53.3 \times 532} = 0.0746 \text{ lb/ft} \cdot 3 \)

The error is thus 0.13 percent at 90 FPS. flow velocity.
CHAPTER VI

PROCEDURE, RESULTS AND DISCUSSION

6.0 General

The phenomenon governing the hydrodynamic flow situation under investigation can be described as follows.

When a turbulent boundary layer is produced by an airflow past a solid surface, the turbulence in the boundary layer can generate a sound field in the free stream and will also induce fluctuating loads on the solid surface. If this surface is flexible, its motion will generate an additional sound field on either side of the surface.

A study of the flow situation indicates that there are two sources of noise generation. The first mechanism of noise generation would be singled out when the wall is absolutely rigid. In that case the boundary layer turbulence will be the only sound source, picked up by the flush mounted ear-bug microphone. The second mechanism of sound generation appears when the wall is flexible enough to deflect under the fluctuating forces imposed by the boundary layer. This would be the case when maniquinn wears a helmet with microphone at the ear canal opening position. In this case the wall motion couples the internal fluid to the external flow field. The resulting motion of the wall causes a sound field in the stationary internal column of air surrounding the
microphone. In the present case we have assumed the following:

1. The helmet wall motion is very small.
2. The weak radiated sound field from the boundary layer will not effect the wall motion, which would be solely governed by the local wall static pressure and the shearing stresses. For the present study only wall static pressure would be considered, since the helmet wall, has the motion essentially normal to the surface.

In an initial investigation of this form of wind generated noise, flow visualisation studies were performed on a model of human head wearing a crash helmet at the test section. The turbulence signal was recorded from areas of serious flow separation and also from attached flow region by a hot wire anemometer. S.P.L. measurement made at the same point in separated flow region by a pressure probe microphone, show a marked similarity between the two spectrums. At ear wind generated noise levels were measured by an ear bug placed within the cavum of the concha.

Following is a step by step procedure and discussion of various noise sources in the wind tunnel and measurement of at-ear aerodynamic S.P.L.

6.1 Wind Tunnel Noise Sources

The model flow noise studies were performed in the open end wind tunnel with construction details as given in Chapter III. The intensity of the turbulence in the test section (with no model) was found to be 1.6 percent and
remained fairly constant as the mean flow speeds were varied from 47 to 85 f.p.s. (Figure 21). The turbulence scale was calculated on the basis of the fluctuating flow component along the axis of flow. Since the velocity profile along the central portion of test section was found to be flat, this turbulence scale is expected to be uniform across the section. The two important effects that had to be watched were reverberation due to end reflections and the background noise level, as they would significantly limit the range of valid acoustical measurements for the proposed flow noise study.

6.1.1 Tunnel reverberation effect

The following measurements indicate the extent of interference due to reflection from the end at the test section.

A small 4" loud speaker with a linear frequency response in the range, 100 to 2000 Hz; was placed 6" from the probe microphone B & K 4134 and 4 mm O.D. 120 mm long tube, that was positioned 0.5" from the helmet at the ear as shown in Figure 22. It was driven with 10-20,000 Hz B&K white noise generator at a level of 100 dB, which is the approximate flow noise level at the R. ear at 90 f.p.s. At no flow condition, the white noise signal was recorded on S.E.8-4 tape recorder and frequency analysed on real time analyser. The result is shown in Figure 23. The white noise level was now increased to 120 dB and the noise picked up by the microphone was analysed and plotted again in Figure 23. It was observed that the terminal reflections did not produce any significant reverberation effect on S.P.L. measurements near the helmet.
from a near field sound source. The tunnel reverberation effect was therefore considered insignificant in the desired range of S.P.L. measurements.

6.1.2 Fan and intake noise reaching test section

In order to estimate the noise from intake and blower reaching the test section, measurements were made with a B&K. 4134 pressure probe microphone with a frequency response as shown in Figure 64. The fan was run at the maximum rated r.p.m. and the intake damper opening adjusted for a flow corresponding to 60 m.p.h. speed in the test section. The probe microphone was placed 1 ft. upstream of the intake damper in the intake plenum chamber, as shown in Figure 38D. The noise was recorded on a "Tandberg" tape recorder, through a measuring amplifier B&K 2607. The calibration signal of 93.6 dB at 1000 Hz was first recorded on tape. This calibration signal was provided by a beat frequency oscillator feeding a loud speaker fitted to an acoustic coupler. The setup was similar to the one used for probe frequency response measurement, as shown in Figure 65. The measured pressure levels were found to be between 111 to 113.5 dBA and 122 to 127 dB linear. Next the fan was stopped and these recordings were played through a B&K. power amplifier to a loud speaker which was placed inside the intake plenum. By adjusting the gain of power amplifier the same levels (111 to 113.5 dBA) were generated at the recording position of the microphone. With a probe microphone and sound level meter the S.P.L. now reaching the test section were measured and
found to be 63.5 dBA. It was therefore concluded that the fan and intake noise is well attenuated by the time it reaches the test section.

The above conclusion is also supported by the results of Figure 24 which shows intake S.P.L. at various flow velocities in the intake plenum chamber at the point shown. The curves in Figure 24 indicate that as the damper is closed i.e. flow speed reduced, the noise levels increase and finally at fully closed damper setting, corresponding to a flow speed of 12 f.p.s. are 100 dBA.

Figure 25 shows the ambient S.P.L. measured at the test section at different flow speeds in the absence of the model. The measurements were made with the probe microphone and a B&K sound level meter. It was observed that the noise increased as the flow speed increased. It should not have been so if the intake noise was significant at the test section as it has been found to decrease with increased flow. Therefore at this stage it was concluded that the equipment noise at the test section was 63.5 dBA; and would be the effective background noise level of the wind tunnel.

6.1.3 Contribution of turbulence to overall microphone output at low flow speeds

The effect of turbulence associated with the mean flow on the microphone output was studied at a point 5 feet upstream of the model in undisturbed flow at the wind tunnel axis. A D.I.S.A. hot wire probe, 1.5 mm long and 5 μ.m. in diameter, was used to probe the fluctuating velocity field in the direction of the flow. Details of the instrumentation,
equipment layout, calibration curves and results are discussed in Appendix I. Because of the small linear dimensions, turbulence measurements were supposed to be unaffected by the presence of the probe up to a frequency where the probe length becomes comparable to half the space wavelength of turbulence, defined as \( \frac{v_o}{f} \) where \( v_o \) is the mean flow velocity in the direction of flow and \( f \) is the frequency beyond which the transducer becomes less sensitive to flow variations.

The hot wire probe calibration was done with a pitot tube and an inclined manometer. The uniform flow was obtained with compressed air flowing through the nozzle as shown in Figure 38C. After obtaining the calibration curves the probe was placed in the wind tunnel as shown in Figure 55. The probe output was measured by a D.I.S.A. hot wire anemometer after balancing the bridge and \( V_{\text{r.m.s.}} \) and \( V_{\text{D.C.}} \) were read on voltmeters. A reference signal of 1 volt \( V_{\text{r.m.s.}} \) at 1000 Hz was first recorded on a S.E. 84 tape recorder from the beat frequency oscillator and following this the turbulence signal was recorded on the tape. This signal was frequency analysed with an audio frequency spectrometer, as detailed in Appendix IB. Figure 40 shows the 1/3 octave turbulence spectrogram at 12 f.p.s. flow velocity with fully closed inlet damper. Low frequency components have been cut off below 22 Hz by filter switching as they could be structurally induced. The spectrum was found to be broad band up to 2 kHz beyond which the spectral amplitudes...
gradually increased, peaking at about 3.5 KHz. and dropping off to the original levels beyond 5 KHz. No suitable explanation could be given at this point for the increase in amplitudes around 3.5 KHz.

As explained earlier, the total fluctuated pressure consists of two components, viz. a quasi sound pressure which is non-propagating and the true sound pressure. It was now considered appropriate to relate the measured velocity fluctuations to sound pressure at a point somewhat remote from the point of measurement of the fluctuating velocity. For the computation of quasi sound, the pressure inhomogeneities may be considered to be frozen while they are carried along the flow at the speed of flow. These steadily moving pressure ripples generate intense nearfield sound but radiate practically no sound to greater distances. However, these fluctuations are picked up by the microphone placed within the flow. The relation between this quasi sound pressure and fluctuating velocity has been derived in Appendix-III and is given as:

\[ p_1 = \delta P(R.M,S) = \rho v_o^* \delta v_n(R.M.S.) \]

A third octave voltage analysis of the turbulence signal at 12 f.p.s. is presented in figure 27. Using \( \delta v_n \) values from this plot at 1/3 octave band centre frequencies, and from the above equation, "\( p_1 \)" was computed at various centre frequencies and plotted in figure 26.
Now the probe microphone B&K 4134 was placed at the same position as the hot wire probe and the total microphone output was measured at 12 f.p.s. flow velocity. The octave analysis of the microphone output is shown by the solid lines of Figure 26. The overall A-weighted levels have been indicated in left hand portion of the plot. A narrow band analysis of the same signal is presented in Figure 28. A slight periodicity observed in the spectrum beyond 800 Hz. could be due to the incomplete damping of probe tube resonances. It was observed that the most important pressure amplitudes exist in the low frequency region up to about 125 Hz beyond which they drop nearly as 12 dB/octave and beyond 1 kHz the microphone output is totally masked by turbulence fluctuated pressure and is broadband in nature.

In order to find the microphone self noise contribution to the above total output; a 4" diameter spherical foam wind screen was placed in front of the microphone. These open cell polyurethane foam screens have been found to reduce the wind noise by 15 dB, where the main frequency range of interest is < 1 kHz. The attenuation of acoustical signal is < 1 dB up to 10 kHz; for 24 m.p.h. flow speeds.

The noise signal measured with the above setup was recorded on a Tandberg tape recorder at 7½ i.p.s. tape speed. A 93.8 dB at 1000 Hz calibration signal was recorded at the tape before and after the measurements. The octave band
analysis of the noise picked up by this wind screen protected microphone is plotted in Figure 26 by the broken lines, curve-B.

Since the turbulence fluctuated pressure was more than 10 dB below the overall microphone output, up to 1 kHz; it was thought that turbulence did not contribute to the overall microphone output up to 1 kHz which therefore represents the overall aerodynamic noise level at that speed. The overall A-weighted noise level was found to be 72 dBA. Beyond 1 kHz the microphone output was found to be masked by the flow turbulence.

6.1.4 Flow noise measurement in empty test section

A pressure probe microphone B&K 4134 was placed 5' upstream of model location in the test section and connected to a B&K sound level meter, model 2209 with an octave analyser. The probe was calibrated with an acoustic coupler as discussed before. The flow speed was measured with a pitot tube connected to an inclined monometer. The flow speed was increased in steps up to 91 f.p.s. and the octave band pressure levels at preferred centre frequencies were as plotted in Figure 25. On the left hand side is shown the overall A-weighted output at different mean flow velocities. It is seen that the aerodynamic noise spectrum does not change in frequency distribution with the flow speed. The pressure amplitudes increase with the speed and the increase is believed to be due to an increase in aerodynamic noise.
generated by the flow, as the fan noise does not change and is more than 10 dB below this level. The S.P.L's are nearly constant up to about 135 Hz, where the space wavelength of turbulence \( \frac{v_c}{2f} \) becomes comparable to the linear dimensions of the microphone and wind screen, and reduce the microphone sensitivity to the turbulence fluctuated pressure. It should be noted that the amplitude deviation starts at lower frequencies at reduced speed. Beyond 250 Hz the amplitudes drop nearly at 12 dB/octave and after 1 kHz they level off as shown by the curves in Figure 25, when the broad band turbulence takes over. Since the tunnel background noise due to the fan is only 63.5 dBA, it was thought that the above S.P.L's measured beyond 30 m.p.h. flow speed were representative of the aerodynamic noise associated with the undisturbed mean air flow.

6.1.5 **Study of the flow noise field at 60 m.p.h. wind speed.**

At this point we could say that the aerodynamic noise levels were mainly responsible for the microphone output at low flow velocities around 12 f.p.s. In order to see if that observation was true even at higher flow velocities, independent S.P.L and turbulence measurements were repeated at the same point, 5' upstream of the model location in mean undisturbed flow at 91 f.p.s. The probe microphone was placed perpendicular to the direction of the flow and its output was measured through a B&K sound level meter and an octave analyser. The octave analysis of the noise has been plotted in Figure 29, Curve-A, along with the overall
A-weighted spectrum level shown at left. This S.P.L. may be composed of pseudo sound pressure, aerodynamically generated sound pressure and the self noise of microphone. The possibility of fan and intake noise had been excluded as the background equipment noise level had been found to be more than 10 dB below the overall spectrum level at this speed. The probe microphone was now withdrawn and the hot wire probe positioned at the same point and aligned 90 degree to the direction of flow. \( V_{\text{r.m.s.}} \) and \( V_{\text{D.C.}} \) components of probe output representing the fluctuating and steady state components respectively were measured by 55 M10 D.I.S.A. C.T.A. and recorded on S.E. 84 tape recorder as described in Appendix I. The reference signal was 50mV\( _{\text{r.m.s.}} \) at 1000 Hz recorded on a tape before and after the turbulence signal.

It was now analysed on an octave analyser. The frequency analysis is shown in Figure 30, on linear frequency base and logarithmic amplitude scale, reference 1 volt r.m.s. The turbulence fluctuated pressure was computed and plotted, as curve-C in Figure 29; using the voltage amplitudes at different octave band centre frequencies, converted to \( \delta v_n \) r.m.s. and the relationship between \( p_l \) (r.m.s.) and \( \delta v_n \) (r.m.s.).

Comparing this with Curve-A it appears that the microphone output at that speed is mainly influenced by turbulence. Beyond about 1080 Hz the microphone becomes less sensitive to turbulence and its output drops below the turbulence fluctuated pressure level. At this frequency the linear dimensions of microphone become comparable to
the space wavelength of turbulence. This probably explains the drop in microphone output beyond 1 kHz. At most frequencies beyond 125 Hz the probe output (curve-A) is within about 5 dB of curve-C showing the turbulence fluctuated pressure. A possible explanation for the difference in response at low frequencies could be the self noise of microphone, and the structural vibrations at the tunnel wall. Its possibility was suggested by the presence of low frequency vibration amplitudes, observed in the vibration spectra, measured at tunnel wall; and presented in Figure 12. To study its effect, the microphone was mounted remote from the tunnel walls through an external frame to isolate any vibrations transmitted to the microphone through the mountings. The noise was measured again, analysed and compared to curve-A. No significant change in spectral amplitudes was observed in low frequency areas below 125 Hz, and hence this possibility was discounted.

The microphone self noise arises from the pressure fluctuations induced by flow over the microphone body. Since the flow direction was well defined it was decided to use a nose cone for self induced turbulence rejection by the microphone. A few nose cones were designed and fabricated with dimensions similar to those commercially available. They were checked in semi free field for the frequency response and the one with widest linear frequency response was used. Figure 31 shows the frequency response of the B&K. 4134 pressure microphone with the grid for normal
incidence and also for the nose-cone protected microphone. It was found that the response was linear up to 1 kHz. It was also observed that the nose cone had attenuated the microphone output about 1 dB at all frequencies. Since our main frequency range of interest was up to 1 kHz this setup was considered suitable enough for the measurements. An octave band analysis of nose cone protected microphone output for 90 f.p.s. flow speed at the measurement location is given in Figure 29 curve-C. The flow noise measured with and without the nose cone was recorded on a Tandberg recorder and frequency analysed. Figure 32 shows the narrow band spectrum of noise measurements. It was observed that the nose cone has reduced the self noise of the microphone by almost 9 dBA. A significant drop in amplitudes was observed throughout the frequency range and the overall microphone response was now found to be within about 5 dB of turbulence fluctuated pressure levels; as shown by curve-B of Figure 29. It was felt that the nose cone had overdamped the microphone sensitivity to mean flow turbulence while successfully rejecting the wall pressure fluctuations produced at the microphone body itself. A better correlation could possibly have been obtained if we had used a sampling tube with highly selective signal response and an efficient turbulence noise rejection. The sensitivity of microphone output to flow turbulence was further demonstrated by positioning the microphone remote from the active area over which the wall pressure fluctuations act, i.e., by placing a spherical 4" diameter foam wind screen in front of the
microphone. The octave analysis of the microphone output so obtained is shown by curve-E in Figure 29. It is seen that the microphone output up to about 135 Hz. is the same as that due to the turbulence fluctuated pressure. After that the space wavelength of turbulence become comparable to the dimensions of the microphone and wind screen and hence the microphone becomes less sensitive to turbulence and it results into a sharp drop in amplitudes which is nearly 10 dB/octave up to 1 kHz and level off after that.

6.1.6 **Comparison of flow noise spectrum measured within the tunnel wall boundary layer and in the main flow**

These measurements were performed 5' upstream of the model location in undisturbed flow. The pressure microphone B&K 4134 was first placed in the flow at the centre of the tunnel and in line with the flow direction. A nose cone was put on top of the microphone for self noise rejection. The microphone output was measured with a B&K 2209 S.L.M. and recorded on a Tandberg tape recorder at 7½ i.n.s. tape speed. An acoustical calibration signal of 93.8 dB at 1000 Hz was recorded on tape from a B&K calibrator. A narrow band frequency analysis of the recorded signal was done on real time analyser in the frequency range 0-2000 Hz. The mean flow speed at the test section was set to 19 f.p.s. by adjusting the intake damper and measured by a pitot tube with an inclined manometer. A flow noise recording was made at this setting, and the analysis is shown in Figure 33, curve-A. The microphone was now removed from the main
stream and placed within the tunnel wall insulation and flush with the tunnel wall, at the same position. Noise was again recorded at the same flow speed, analysed and plotted in Figure 33 curve-B. The spectrum of noise shows practically no change in amplitudes as well as frequency content, which essentially consists of low frequencies up to 200 Hz. The overall S.P.L.s remain unchanged at about 73.2 dBA which is the aerodynamic noise level at this speed. It suggests that pseudo-sound pressures from flow turbulence do not significantly effect the microphone output at this speed, and that it is solely governed by the aerodynamically generated acoustic sound pressures propagating at the speed of sound.

Now the microphone without the nose-cone was placed at the same point as before, flush with the tunnel wall, and the noise was measured at 19 and 91 f.p.s. to determine the effect of change of speed on noise field outside the main flow, within the wall boundary layer. The narrow band frequency analysis of the noise measured at the above speeds is shown by curves A and B of figure 34. It clearly show that the spectral composition of noise does not change significantly with flow speed, but the pressure amplitudes increase from an overall 73.2 dBA to 85.5 dBA. This increase in levels is believed to be due to an increase in aerodynamic noise at higher flow speeds. Now the microphone was placed back in the main flow along the direction of the flow and was protected by a nose cone. The measurement location was the same as before i.e. 5' upstream of the model location in the test
section. The flow noise was recorded again at 19 and 91 f.p.s. and frequency analysed. The spectrum is shown in Figure 35, with overall dBA levels indicated in the top right hand portion. It is seen that a similar increase in flow speed produces almost three times as much noise increase as in the wall boundary layer. The overall S.P.L. had increased from 75.4 dBA to 103.3 dBA. Thus it is believed that while the microphone output outside the main flow stream is mainly influenced by the radiated acoustic field; the microphone placed within the flow responds to both, the pseudo sound and the aerodynamic noise from turbulence. Also it can be observed that with an increase in flow speeds, the increase in pseudo-sound is much more than the increase in aerodynamically generated noise; for a microphone placed inside the main flow. Thus the pseudo-sound has a masking effect on noise from other sources. Finally, the overall narrow-band analysis of wind generated noise at 90 f.p.s. in an open test section is presented in figure 35A. The overall sound pressure level is found to be 103.5 dBA. Most spectral energy is seen to be contained in low frequency region up to 500 Hz.

6.1.7 Effect of introducing the model in test section

It was now decided to study any change in the local sound field produced as a result of the introduction of the model at the test section. The model is believed to be an additional source of noise due to the existence of turbulent wall boundary layer set up. To study its effect on aerodynamic noise measured within tunnel wall boundary layer,
A B&K 1/2" pressure microphone model 4134 was mounted flush with the tunnel wall at the test section and at the ear level. The mannequin was wearing a helmet and visor. At 90 f.p.s. flow velocity at the test section, noise measurements were made with and without the model at the test section. An octave analyser connected to the B&K 2209 sound level meter (S.L.M.) provided the octave analysis of the signal which is presented in Figure 36. It was observed that the S.P.L. decreased up to about 750 Hz and an increase was observed beyond that. It is interesting to observe that the overall noise level has dropped by about 3.5 dBA from 94.2 to 90.8 dBA. A possible explanation for this decrease in aerodynamic noise could be the increase in local flow velocity due to the introduction of the model at the test section resulting in lower turbulence levels and hence a decrease in aerodynamic noise levels.

6.1.8 Transmission of noise through the helmet walls

When the turbulent flow exist at the helmet surface, there is in addition to the radiated acoustic field; a transmission of sound through the helmet wall due to its vibrations. The helmet surface acts as a coupling between the wall pressure fluctuations existing outside the helmet and the medium inside the helmet. Therefore when a microphone is placed inside the helmet it seems to act as if the entire helmet surface was its active area. The reduction in aerodynamic noise levels due to the helmet wall attenuation is expected to be largely compensated by the
focusing effects of the surrounding boundary layer noise by the helmet wall. The reverberation effect due to wave interference were therefore expected to reproduce themselves as peaks in noise spectrum measured inside the helmet.

To observe this effect an ear bug microphone was mounted flush at the right hand ear canal opening position on the mannequin wearing a helmet and visor. Suitable input attenuation was used to provide a linear dynamic range from 85 to 115 dBA. A calibration signal of 93.6 dB at 1000 Hz was provided from a B&K calibrator and recorded on tape before and after the recordings. The A-weighted output of the earbug was analysed on a real time analyser. The ear bug output was recorded at 91 f.p.s. flow velocity; analysed and is shown in Figure 42. The wave interference effect can be clearly observed in the microphone output.

6.1.9 Study of flow pattern and turbulence spectrum at the helmet wall

Since the flow turbulence is the source of aero-dynamic noise and because the turbulence at the helmet boundary layer would be different than that associated with the mean flow as measured earlier; it was decided to investigate it in detail. Flow visualisation studies were carried out using oil flow technique to locate areas of flow separation. The method used for visualising the flow at low Mach number consists of coating the helmet surface with a suspension of finely divided Titanium oxide (100 gm) in 135 c.c. of liquid Paraffin with about 2 c.c. of Oleic
acid. When the wind is turned on, liquid flows over the surface. Eventually the liquid paraffin is blown off but its previous motion is shown and preserved by the deposition of powder on the surface. The pattern is then photographed. Such flow patterns obtained at 90 f.p.s. at the test section with helmet and plane visor are as shown in Figure 38E.

These pictures give a general qualitative idea of relative magnitudes of local velocity distribution over different parts of the helmet. In the area of no complete full chord separation it is thought that the oil pattern yields a good qualitative picture of the flow in boundary layer. The picture shows the regions of serious flow separations and the attached flow regions. On the forehead position the presence of strong spiral vortices can be observed. On the sides it appears that the paint has moved against the direction of flow suggesting that it may be responding to pressure gradients on the wall and seeks the peak suction position. In the wake however, the flow is completely detached and the presence of gravitational flow in the absence of inertia effects is observed.

Since it has been reported that high aerodynamic noise levels are a consequence of various forms of flow separation and particularly the noise attributable to vortex flow is very loud; it was decided to measure the turbulence spectrum in the area of attached and separated flow. Measurements were made with 5 μm x 1.5 mm long constant temperature D.I.S.A. hot wire probe, placed at
position #1 and II (see Figure 38E) and traversed outward perpendicular to the surface. The frequency analysis of the voltage signal is shown in Figure 39 and 41 at the two probe locations. The spectrum was found to be broad band with major amplitudes in the low frequency region below about 1 kHz, beyond which the spectrum levels off. Refering to Figure 39, it can be seen that as the probe is moved away from the wall, the spectral amplitudes increased with practically no change in spectral distribution. The amplitudes peak at a distance of about 1" and then start dropping until at about 2" outside the boundary layer the amplitudes drop off to the ½" distance levels existing inside the boundary sub layer. In the attached flow region, refer Figure 41, a slightly different distribution is observed. Close to the boundary wall, at ½" distance, the spectrum remains unaltered. However, as the probe is moved away the amplitudes reduce and drop off more rapidly, and beyond about 1" become practically independent of probe position. Thus it is observed that much higher spectrum levels are encountered in the region of separated flow as compared to the attached flow region. Table number I-T-4 page-135, shows the intensities of turbulence encountered at these two positions at different probe locations. It was found that the turbulence scale was much higher, 6.6 percent in separated flow compared to 2.2 percent at the same distance in attached flow region; while the turbulence scale of undisturbed flow was found to be only 1.6 percent.
Since the pressure response of a microphone in near field is mainly governed by local velocity fluctuations we may expect that high aerodynamic noise levels are a consequence of flow separation. In particular, the noise attributed to the vortex flow, resulting from flow separation at the leading edge of the helmet, could be considerably higher than the noise level due to attached flow.

Having studied the wall pressure fluctuations, it was decided to measure the total pressure field at the ear canal opening position, with and without the helmet on the mannequin's right hand ear.

6.1.10 Acoustical calibration of the wind tunnel

In order to correlate any noise measurements performed in the wind tunnel to those in free field, it was found necessary to plot the calibration curve of the wind tunnel. It was obvious that the presence of close boundaries keeps the noise from propagating and diffusing as it happens in the free field. This effect was expected to yield slightly higher sound pressure levels in the wind tunnel. The calibration was performed experimentally by measuring the noise field of a point source, a small 4\" diameter loud speaker whose frequency response was found to be linear up to 2 KHz, in the test section as well as in the free field. The microphone was mounted at the test section at the place of the mannequin facing upstream. It was driven by a white noise generator through a B&K power amplifier, producing approximately 110 dBA at the microphone position. The probe
microphone was placed 1" from speaker facing it along the tunnel axis. The probe microphone was traversed along the axis and the sound pressure levels were measured at each position. The loud speaker was then removed and placed in a semi free field and similar measurements repeated. The S.P.L.s obtained are plotted in Figure 46. The sound pressure field was found to be symmetrical about the source position and decreases inversely with distance. The S.P.L.s inside the tunnel being always higher than those in the free field at similar measurement locations. To study the noise spectrum an octave analysis was carried out on the above noise measurements made at a distance of 6" from the source both inside and out of the tunnel. The results are plotted in Figure 47. The frequency distribution shows that the tunnel becomes noisier at certain frequencies with respect to the free field source levels and quieter at other frequencies. Beyond 2 kHz there is no difference between the noise measured in the wind tunnel and in the free field.

In the present study the above calibration data has not been applied because these measurements were performed with the transducer placed in close proximity of the noise source, which was the flow turbulence. As shown by figure 46, close to the source region the two curves read almost the same and no correction would be needed. However, if the measurements were to be performed in this wind tunnel at some distance from the source, it would be relevant to apply this correction.
6.2 **At Ear Measurement of Acoustic Pressure Field**

The overall noise levels were measured with a probe microphone B&K 4134 fitted with a probe tube and placed outside the helmet ½ inch from surface at the right ear position. The flow noise spectrum at 90 f.p.s. velocity is shown in Figure 37. The spectrum shows the predominant pressure amplitudes existing in low frequency area below about 1 kHz. The amplitudes drop off inversely as approximately the cube of frequency and level off beyond about 1.5 kHz. The sinusoidal variations observed beyond this frequency are expected to be due to the incomplete damping of the probe tube resonances. In general there seems to be good amplitude similarity in the low frequency region between the spectrum and the corresponding turbulence spectrum measured at the same half inch distance from helmet wall as shown in Figure 39.

A time averaged narrow band analysis of A-weighted sound as measured inside the helmet with a flush mounted ear bug microphone at the right ear position was found as shown in Figure 42. The overall sound pressure level was observed to be 103 dBA at 91 f.p.s. flow velocity, at the test section. The pronounced periodicity in amplitudes suggest the presence of reverberation effects inside the helmet.

6.3 **The Overall A-Weighted Noise Measurements at Various Flow Speeds**

Figure 48 shows the noise measurements as a function of flow velocity. Curve-1 indicates the background wind tunnel noise measured in the test section with no model in the test section. The tunnel background noise is found to
increase linearly and reaches a level of 91 dBA at 91 f.p.s. As discussed before the spectrum of this noise is rich in frequency components below about 125 Hz, and drops off rapidly beyond that. Below about 40 f.p.s. the aerodynamic noise from the fan is prominent while beyond that the background noise mainly consists of broad band turbulence fluctuated pressures.

Curve-4 shows the noise field measured at the ear canal opening position with a flush mounted earbug microphone placed at the right hand ear canal opening. In this set-up the wind direction was normal to the mannequin and the outer ear was absent. It should be noted that the presence of pinna would introduce some pressure gain in the frequency range 1.6 to 6 kHz. Now it was decided to introduce the large helmet and measure the microphone output at different speeds. The effect of noise attenuation produced by the helmet is found to be quite significant; almost 12 dBA at 91 f.p.s. as shown by Curve-3.

Refering to Figure 48 Curve-2, which shows the at ear noise measurements with a large size helmet and a plane visor and the ear bug mounted flush at the right ear canal opening of the mannequin, a further reduction in the overall noise levels experienced at the subjects ear was observed. The presence of a visor essentially amounts to a further streamlining of this bluff body submerged in flow and reduces the flow separation resulting in lower turbulence levels, which are essentially responsible to the mechanism of sound generation.
6.4 Effect of Flow Direction on Sound Measured at Ear

Having measured the sound field present at the ear, it was decided to study the change in noise field at ear due to the motion of subjects’ head with respect to the flow direction; in the horizontal plane. Figures 48A and 49 show such directivity effects at different speeds and with different visors. In order to exclude any fixed errors, measurements were always made at the right ear position. The indexing was repeated and the spread of data was found to be within 1 dBA at any incidence and the mean values were plotted.

It can be observed that a curved “bubble” visor results in generally lower sound levels, and the measured difference is more significant at lower speeds (≤ 30 m.p.h.) where we may expect up to 4 dBA reduction, while at 60 m.p.h. the reduction is only 2 dBA for normal incidence. Another point to be observed is the relative change in the angular position of the bulge in the directivity curve with the flow speed. Ideally we should prefer a visor that would produce the least change in microphone output for a head movement of ± 30° either side of the direction of motion. Although at higher velocity (≥ 60 m.p.h.) both the visors produce nearly similar change (= 3 dBA); at lower velocity (≤ 30 m.p.h.), a curved visor shows little azimuthal dependence (within 1 dBA), and should certainly be preferred.

Next the sound levels at the right and left ears were measured simultaneously as a function of head position relative to the direction of motion. Significant changes
were observed between the left and the right ear bug response, ranging from 0 to 5 dBA as shown in Figure 50. However, it is interesting to note that within a range of ± 30° both right and left ears received nearly identical sound levels within 2 dBA.

Next it was decided to measure the at ear flow noise levels with helmet and without visor, at different flow speeds and at different angles of incidence. The flow was altered by controlling the inlet damper openings and the noise measurements were repeated at the right ear canal opening position with the ear bug for 0 to 360° indexing. The change in noise levels observed is shown in Figure 51. Pronounced directivity effects were observed at low speeds and as the flow speed increased these S.P.L. variations diminished. At full intake damper openings, the change in response due to directional effects was within 1.5 dBA for ± 60° range and within 2 dBA in most of the other locations except around 90°, where a maximum drop in sound level of nearly 6 dBA was observed.

6.5 Effect of Forward Inclination

Next it was decided to study the effect of inclination of rider in the forward direction upon the noise field at the ear. The measurements were taken at 5 degree intervals from straight upright position to 45 degrees bent over position, and each measurement was repeated at three different horizontal positions of 0°, 90°, and 270°; considering the effect when the rider bends forward and looks sideways. The measurements
were taken at the right ear canal opening position with the ear bug. The results obtained are shown in Figure 52. It can be seen that no significant variation in noise levels exists for the head inclination in vertical plane upto 20 degrees. Beyond this the variation increased and is particularly significant (about 7 dBA) beyond the 35 degree bent over position in case of normal incidence; as shown by curve-C in Figure 52. Hence one may expect that the rider could experience significantly lower sound pressure levels by bending over in a forward direction.

6.6 Effect of Shape and Geometric Dimension of Outer Ear Upon S.P.L. at Cavum at Constant Speed and Orientation

A pair of rubber replicas of the external ear with a pinna, concha and auditory meatus having dimensions comparable to those of real human ears have been tested. The dimensions and shape are as shown in Figure 56B and Figure 38G. At the eardrum position, there is a provision of a reflecting baffle, whose acoustic impedance is unknown. The replica had been mounted at the right ear position on the manequinn. The wind generated noise was measured for normal incidence, at 90 f.p.s. flow velocity. The S.P.L. was measured with an ear bug system having an input attenuator providing a suitable dynamic range. Measurements were performed on both the ears under similar conditions at both cavum and ear canal opening; and the results are shown in Figure 57. It is observed that the minor difference in geometric dimensions of the outer ear does not produce any significant
difference in wind noise levels received at both cavum and ear canal opening with blocked meatus.

6.7 Variation of S.P.L. from Point to Point Within the Cavum

S.P.L* measurements were made to evaluate pressure distribution within replica cavum due to wind noise for frontal incidence, at any flow speed. The measurements were performed at 90 f.p.s. with blocked meatus and the results are shown in Figure 56, for three different probe microphone positions as shown in Figure 56B. The results indicate nearly uniform pressure distribution within the cavum.

In order to find out if this is also true for the free field measurements with no wind flow, similar measurements were made under free field with a white noise source. The equipment layout is shown in figure 58. A 20 KHz. white noise was generated by noise generator (B&K model-1405) and played via a power amplifier through a university sound model ID-60, 60 watt r.m.s. loud speaker. The distance between microphones and loud speaker was 4 feet, sufficient enough to avoid any source proximity errors in the wave front.

At first, the sound field was monitored at the same point by ear bug and the probe microphone in free field. The non linearity in frequency response of probe microphone was within 2 dB, up to 1.5 kHz as shown in Figure 64. The measurements indicate that the ear bug output was 2 dBA higher than the level indicated by the probe microphone. Now the ear canal was blocked by the ear bug and a constant

* Sound Pressure Level

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level of 90 dB was set by the probe microphone inserted into the cavum.

The probe was now moved to six different positions in the cavum as shown in Figure 56B. The variation in S.P.L. within the cavum was found to be less than 1 dBA. Now we put the probe microphone just near the ear bug at the ear canal opening and adjusted the sound field at 90 dBA at that point. Simultaneously, the ear bug output was also monitored. Again it was found that the ear bug reading 2 dBA higher than the probe reading. This suggests that in free field with no wind flow, S.P. levels at the cavum do not vary by more than 1 dBA and are essentially the same at the ear canal opening position with blocked meatus. The 2 dBA variation was found to be due to the combined effect of room reflection error and non linearity in probe response.

6.8 Effect of Blockage of Meatus on Sound Pressure Measured at Ear Canal Opening

These measurements were performed in semi free field conditions with a probe tube fitted pressure microphone, B&K 4134. The tube dimensions were 2 mm outside diameter and 120 mm in length. The measurements were plotted as ratios of pressure at the measurement location to the pressure at the centre head position, in the absence of the subject. Thus the non linearity effects introduced by the probe tube response have been eliminated. The frequency response of ear to normal sound incidence in free field was found to be as shown in Figure 59. Significant acoustic gain was observed
at about 2.7 kHz. This is believed to be due to the resonance in the ear canal. The following pressure minima may be due to the standing wave minima existing at $l = \frac{\lambda}{4} = 2.3$ cm; 'l' being the length of ear canal used. Subsequent pressure minima were expected to occur at higher odd multiples of $\frac{\lambda}{4}$. However, it is observed that with the meatus blocked; a maxima occurs at about 4 kHz, which is believed to be due to depth resonance produced by the cavum and was found to be broad frequency based. Thus the effect of blockage of the ear canal was to increase the fundamental resonance frequency (since there was no resonance produced in the ear canal) and a decrease in resonant pressure amplitude at the ear canal opening. The maximum amplitude of first pressure maxima existing at 2.7 kHz has been observed to be 19 dB; which is typical of the real human ears at this frequency under similar conditions, Reference 22. However, the comparison is not so good at frequencies below 1.5 kHz, where the typical response of real human ear is about 5 dB. This discrepancy is probably due to the fact that the eardrum impedance is mainly capacitive at lower frequencies instead of purely resistive. Hence a better corelation could have been obtained by venting the eardrum resistance into an enclosed coupler cavity.

Figure 59A shows the response of the ear replica at normal incidence with hard wall ear drum versus frequency, obtained by Shaw. Qualitatively the two results show a similar effect of the meatus blockage viz. the first resonance peak shifts to a higher frequency and turns into broad band as a result of the blockage. The peak amplitudes were found to be nearly
the same, although Shaw observed the first resonance peak at about 3 kHz while in our case it was observed to be around 2700 Hz. This discrepancy could be due to the shorter ear canal length used by Shaw. A quantitative comparison cannot however be made because of the significant difference in test model geometry, method and representation of results. These included sound source distance, ear canal length, diameter, ear drum impedance, non spherical wave front and different reference pressures.

6.9 **Pressure Transformation from Free Field to Ear Drum**

The combined effect of pressure gain produced by the diffraction from the head, outer ear and resonance in the auditory canal was obtained by measuring pressure transformation from free field to the ear drum, and was found to be as shown in Figure 60 for the mannequin, with frontal sound incidence. The pressure transformation is given in terms of the ratio of sound pressure at the ear drum to pressure existing at the centre head position in the absence of the mannequin, expressed in dB. The sound pressure at the eardrum was measured with the probe microphone inserted into the ear canal from outside, till it touched the diaphragm. The set up was similar to the one shown in Figure 50 except a beat frequency oscillator was used instead of white noise generator. It was observed that up to about 600 Hz, there was no significant acoustic gain produced with respect to the free field. Beyond that the sound pressure at the ear drum was substantially greater than the free field pressure, and the first resonance appears at
about 2700 Hz with a peak amplitude of 18 dB, which is identical to the fundamental resonance of the ear canal as shown in Figure 59, Curve I.

Figure 60 also shows the data from the pressure transformation curve obtained by Shaw and Weiner on a group of live subjects tested in an anechoic chamber for frontal sector, 0°azimuth and pure tones. They reported an inter subject standard deviation of 1 dB up to 500 Hz increasing in an erratic fashion to over 5 dB above 5,000 Hz. Both the results show a positive pressure transformation throughout the frequency range. The fundamental resonance occurs in both cases at about 2700 Hz with a peak amplitude of 17 dB. Significant variations between the results, particularly at 3 kHz and beyond could be due to the variations in the shape, size and protrusion of the pinna flange which has been found critical between 2 and 6 kHz.

6.10 Pressure Transformation in Auditory Canal

Since all the pressure measurements have been made at the cavum, it was necessary to correlate these sound pressure levels to those existing at the eardrum position. By placing a microphone at the cavum and comparing the sound pressure there with the free field pressure, the total obstacle effect of head and pinna is arrived at. Adding to this the pressure increase in the ear canal would result in a measure of total pressure transformation from the free field to the ear drum. Sound pressure ratio between the ear canal opening and the ear drum, obtained for the mannequin,
with a probe microphone and a similar set up as discussed before under semi-free field and normal incidence was found to be as shown in Figure 61. No significant acoustic gain is observed till about 1 kHz and a peak pressure gain of about 11 dB occurs at 4 KHz.

Figure 61 shows the results obtained by Shaw and Weiner on pressure transformation produced in the auditory canal for live subjects. The comparison is found to be very satisfactory over the whole experimental range.

6.11 Comparison of Wind Generated Noise Levels Measured With and Without the Outer Ear

In order to compare the effect of the outer ear on the flow noise measured at the ear canal opening position, the data of Figure 48 was superimposed on the measurements shown in Figure 62 and 63, which are without and with the helmet respectively. A very good agreement is observed throughout the velocity range in the case of Figure 63 which was with the helmet. However, the agreement is found not so good in the case of "no helmet", particularly beyond about 80 f.p.s. where the deviation is up to five dBA. This supports the argument presented in Article 6.12.

6.12 Typical Wind Noise Levels Obtained at the right Ear Cavum and Ear Canal Opening

The r.m.s. values of typical S.P.L. obtained at the cavum and ear canal opening at different flow speeds is as shown in Figure 62. These measurements had been made with ear number 1 and without the helmet. The ear bug was
protruding 1/8 of an inch out of the ear canal. It was observed that S.P.L's at cavum were higher than at the ear canal opening at all speeds. There seemed to be a constant transfer function of about 7 dBA existing beyond about 60 f.p.s. flow speed. It was also observed that the wind noise levels increase up to about 60 f.p.s. and become constant thereafter. Since it has been previously observed that there exists no pressure variation between the cavum and the ear canal opening (with blocked meatus) at zero flow condition, the observed drop of ≈7 dBA in S.P.L. at the ear canal opening is expected to be due to the difference in turbulence field at the two locations. It was further observed that the position of the earbug microphone was critical and significantly effects the levels at the ear canal opening. Withdrawing the ear bug microphone ½ inch or more out of the ear canal, cause the indicated S.P.L's to become independent of the microphone location in the cavum.

Sound pressure levels were also measured at the ear canal opening and the cavum with the mannequin wearing a large size helmet, to find the effect of the helmet. These measurements (Figure 63) were made for frontal incidence and flow speeds ranging from 30 to 100 f.p.s. Two ear bug microphones were used, one mounted flush with the ear canal opening and the other placed in the cavum with a clip. It was found that the S.P.L. at the cavum was essentially the same as that at the ear canal opening, over most of the flow range. The curves roll off beyond about 90 f.p.s. indicating the independence of S.P.L.'s over flow at high speed. This
trend was similar to the one observed with no helmet (Figure 62), except that in that case the roll off started at a lower flow speed.

6.13 Comparison Of Wind Tunnel Measurements with Free Field Wind Noise Measurements On Motorcycle Riders:

In order to compare the results obtained on the model in the wind tunnel with the actual measurements of noise exposure of motorcycle riders; repeated highway runs were carried out. In this study five different makes of bikes, of various horse power ranges (both two and four stroke) were driven by different riders. The runs were partly in the city and partly on country highways. The vehicle speeds on the highway were maintained at 55 m.p.h. The riders were using appropriate helmet and visors which best fitted them. At the cavum of the right ear of each rider an ear bug microphone was positioned as shown in Figure 38F-2 and it was coupled to the tape recorder through an input attenuator to give a continuous record of sound pressure levels. A 93.6 dB at 1000 Hz calibration signal was recorded on the tape before commencing each run. Near the right ear concha a B&K 4125 microphone (of noise dosemeter) was positioned and was coupled to an O.S.H.A. weighted noise dosemeter. The microphone position was as illustrated in Figure 38F-1. The indicated percent noise dose (obtained in 'ON' mode) were converted to $L_{eq}$ levels by the procedure described in Appendix 4. The earbug recordings were played back through the logarithmic spectrum equaliser, which was
set to shape the signal to Type II A-weighting, and statistical distribution analyser, and to the level recorder. Histograms showing the distribution of $L_{eq}$ versus time for two motorcycles tested are shown in Figures 53 and 54.

While comparing these results with those of Figure 63 obtained in the wind tunnel, it should be noted that the later results were obtained with the mannequin wearing no visor, which has been found to reduce the S.P.L's by 2 to 3 dBA. Allowing for this effect, the highway test results show a good agreement with the results obtained in the wind tunnel at the corresponding speed. Recently more tests were conducted on riders doing motorcycle runs on highways under controlled conditions at constant speed of 50 m.p.h. Also constant speed tests were carried out at different speeds and gear settings, on a test track. The results are presented in Figures 66 and 67 respectively.

In these measurements the maximum inter subject variation was observed to be up to 8 dBA. This variation was similar to that observed in measurements on live subjects in the wind tunnel. The maximum run to run variation was found to be within 2 dBA. The mean S.P.L's on highway runs were found to be generally lower than the corresponding wind tunnel measurements by about 7 dBA. This excludes the intersubject variations. The reason for higher S.P.L's on the mannequin could be the loose helmet fit which has been found to enhance the noise levels.
6.14 Comparison of Wind Noise Spectrum

A narrow band analysis of the A-weighted noise signal output of the ear bug was carried out in the frequency range 0-2 kHz. The purpose was to compare the wind noise spectrum obtained at the right hand ear inside the helmet in the wind tunnel to that obtained on live subjects in the outdoor highway runs. In the wind tunnel measurements the ear bug was worn by the mannequin flush at the right hand ear canal opening with no pinna while the subject wore it with a clip, such that the bug was placed in the cavum of the concha just outside the ear canal opening. The wind tunnel measurements are shown in Figure 42 at 91 f.p.s. flow speed while the highway runs were performed at the maximum speed of 50 m.p.h. and the spectrum is shown in Figure 43. It was observed that the at ear noise spectrum obtained in the wind tunnel was similar to that obtained in actual motorcycle highway runs with regard to frequency distribution. The prominent peak in Figure 43 at 150 Hz was assumed to be corresponding to the engine firing frequency. The difference in spectral amplitudes of Figures 42 and 43 was due to different speeds at which measurements were made and the variables involved in the highway run including wind direction, speed and rider position etc.

6.15 Comparison of the Results with Harrison, Swaney et al., Outboard Marine Inc., and van Moorhem's Findings

Before comparing these results, the various transducers and measurement methods employed by the above investigators should first be discussed, since they could significantly
effect the results. Research conducted by Swaney et al. involved a brief investigation of noise generation due to air flow over the helmet in a wind tunnel with a styrofoam wig head at speeds ranging from 13 to 53 f.p.s. The microphone (type not revealed) was placed inside the head and at the end of an artificial ear canal.

Harrison's instrumentation involved a B&K pressure microphone type 4134 fitted with a probe tube and connected to a S.L.M. The probe tube end was placed externally near the ear canal opening on a live subject and held in position with masking tape.

The results of the Outboard Marine Inc. were obtained by an "ear bug" placed in the cavum of concha of live subjects riding in the back of a moving truck. The ambient S.P.L. was estimated to be 60 dBA while coasting.

Van Moorhem used a half inch microphone placed adjacent to the auditory canal of live subjects riding a motorcycle. The microphone was connected to a precision S.L.M. and a tape recorder. Background noise levels were measured with a B&K nose cone fitted microphone.

Harrison has reported motorcyclists at ear noise levels of over 100 dBA at moderate speeds with the rider bareheaded or wearing a helmet. He concluded that at speeds below about 59 f.p.s. the majority of noise experienced was radiated from machine itself, resulting in very little helmet attenuation while the aerodynamically generated noise attenuation at higher speeds (>90 f.p.s.) was up to 15 dBA. The results in Figure 62 and 63 show a wind noise reduction.
of 10 dBA over the no helmet condition. The reduced attenuation could be the result of poor helmet fit on the mannequin and the type of helmet used. However, at low speeds the hearing protection capability of the helmet, from aerodynamic noise was found to be particularly good. This was in contrast to the findings of Harrison, which may have been influenced (as claimed by van Moorhem\textsuperscript{56}) by the presence of low frequency tonal noise from his high performance off street motorcycle. This type of noise could pass through the helmet without significant attenuation. In our case the noise source was purely aerodynamic, mainly the boundary layer turbulence, which had a broad band frequency spectrum, and was significantly reduced by the streamlining effect produced by the helmet over the bare head situation.

Figure 65A shows a comparison of the bare head noise measurements with those of above mentioned investigators, as a function of flow speed. Our results show very good agreement with those of Harrison and Swaney up to 53 f.p.s. Swaney reported his results only within a flow range of 13 to 53 f.p.s., which were obtained in the wind tunnel, under essentially identical conditions. Beyond about 55 f.p.s. our results show no significant increase in S.P.L. with speed unlike R.T. Harrison's results, which show a continuous increase in levels with speed. The Outboard Marine Inc. data does not compare favourably with any of the above studies. However, it shows a roll off beyond about 90 f.p.s. which agrees with the general trend observed in our results at that speed. After listening to Harrison's tapes of O.R.V.
noise, Van Moorhem indicates the audibility of gear shifts, implying that much of the measured at ear noise was generated by the motorcycle itself. This could be the reason for the discrepancy between Harrison's and our results beyond 65 f.p.s.

Assuming the main noise source is the boundary layer noise, and the flow undergoes a transition from laminar to turbulent flow at about 50 f.p.s. for the flow around a smooth sphere of the size of a human head, the transition occurs roughly where the S.P.L. become independent of speed. It is believed that after the flow becomes completely turbulent the fluctuating velocity component \( \bar{\nu} \) become independent of the mean flow velocity at the same location and hence the S.P.L's do not increase.

Figure 65B compares the results obtained with the helmet. The difference between Harrison's data and van Moorhem's results is rather conspicuous. At-ear levels measured by Harrison show a very small increase with velocity, which is considered inaccurate due to the reasons stated above. Noise due to turbulent flow around a solid boundary of the size of the helmet would be expected to increase approximately 18 dB for each doubling of velocity. Our results show a similar linear increase in noise levels with flow speed. Van Moorhem's results were consistently lower than ours. A possible reason for the variation could be the difference in helmet fit which is found to cause higher attenuation if worn tight; and the presence of a wind shield on the motorcycle which may well have kept the rider in his study within boundary layer in a crouched position; hence causing lower noise exposure. Also
the large size of the microphone (half inch) used by Moorhem at the ear is obviously expected to interfere with the at-ear noise field. Moreover, the effect of the visor is to reduce the S.P.L. by 2-3 dBA which was used in Moorhem's study.
CHAPTER VII
CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions:

The important results of this study have been summarised below.

1. At flow velocity less than 20 FPS, aerodynamic noise is the major source of noise. It is prominent in low frequency bands up to about 250 Hz.

2. Turbulence fluctuated pressure increases with the mean flow speed, and at speeds greater than 90 FPS, it completely masks all other sources of noise.

3. The flow field around the head is highly turbulent. Within the helmet wall boundary layer, the turbulence levels change with the distance normal to the wall. The turbulence and noise spectrum is remarkably similar in this region. The SPL's in the vortex flow region are nearly 10 dB higher than the corresponding levels in the attached flow region.

4. The helmet is effective in reducing the wind noise at all speeds. The insertion loss at 90 FPS is 12 dBA. At speeds lower than 60 FPS, the insertion loss is greater.

5. The effect of a visor is to reduce the noise exposure by 2 to 3 dBA.

6. The at-ear noise is highly directional. The directivity effect however reduce at higher speeds. At 90 FPS, flow velocity and normal incidence, the difference in noise levels between right
and the left ear may be upto 2 dBA. For a head movement of $\pm 30$ degree in the horizontal plane, the change in noise level at the same ear may be upto 3 dBA.

7. The effect of crouching in the forward direction is to reduce the noise exposure at ear. It has been observed that for about 35 degrees head inclination in the forward direction, the reduction in noise level may be upto 7 dBA.

8. There is no significant point to point variation in the observed noise levels within the cavum of the concha at speeds greater than 60 FPS.

9. The geometric dimensions of pinna have no significant influence upon the observed noise levels at the cavum of the concha.

10. Sound pressure levels measured at the ear canal opening are essentially the same as those at any other point within the cavum of the concha, at mean flow speeds 60 FPS. and beyound.
11. The pinna and ear canal together produce a positive pressure transformation over most of the audio frequency range, on the progressive sound waves reaching the outer ear. The maximum gain is of the order of 19 dB. at about 2700 Hz.

12. The effect of the blockage of ear canal is a shift in the fundamental resonance from 2700 Hz. to a broad band resonance, centered at 4 KHz. This is coupled with a decrease in resonance amplitude by 8 dBA.

13. Wind generated noise levels measured at the ear, increase with the mean flow speed and at 90 FPS. is 116 dBA. at the cavum of the concha and 109 dBA. at the ear canal opening. Beyond about 60 FPS. the curves roll off and there exists a constant transfer function of about 7 dBA. between the sound pressure levels at the cavum of the concha and the ear canal opening.

14. The presence of helmet eliminates the constant transfer function; and the observed sound pressure
levels at ear canal opening and the cavum become essentially the same over most of the above speed range.

15. The above results obtained in the wind tunnel, agree within 5 dBA. with the $L_{eq}$ computed from the free field measurements made on the subjects riding motorcycles. The effect of aerodynamic shaping and reduced turbulence upon the noise measured at the ear has also been confirmed by the free field tests on these subjects.

7.2 Recommendations:

Following are some suggestions that may be considered in order to improve upon the performance of the present test facility, and to obtain a better correlation between the wind tunnel and the free field noise data.

1. As a result of a 90 degree bend in the flow direction, there is a considerable amount of turbulence introduced in the flow. A reduction in this could be achieved by introducing a bank of acoustically lined corner vanes at the bend. This would reduce the turbulence associated with the mean flow and the aerodynamic noise levels.

2. The subjective highway noise measurements should be more restrictive, and should preferably be limited
to no ambient wind flow conditions. A replay of the taped noise indicates distinct external wind noise; causing substantial variations in noise levels.

3. The riding position should not be altered during the run.

4. Pressure transformation has to be performed on the measured wind noise levels at cavum to convert it to the levels existing at the centre head position; in order to compare them with the existing noise evaluation and hearing protection regulations which specify diffused field at the centre head position in the absence of the listener.
TURBULENCE PRESSURE FLUCTUATION MEASUREMENT USING CONSTANT TEMPERATURE HOT WIRE ANEMOMETER

General

D.I.S.A. 55M system with 55M10 CTA standard bridge constant temperature anemometer has been employed for measuring instantaneous mass flow of air using D.I.S.A. miniture hot wire probe 55P11, (Ref. Figure 55). Bridge output was connected to D.I.S.A. type 55D30 digital voltmeter for mean flow velocity indication and D.I.S.A. type 55D35 r.m.s. voltmeter for measuring r.m.s values of velocity fluctuations. The C.T.A. output was also connected to a S.E. eight-four tape recorder for recording turbulence spectrogram on B&K level recorder 2305. The instrumentation has wide dynamic range and was found suitable for measuring turbulence components from 0.1 Hz to 700 kHz range.

Probe Characteristics

The use of hot wire sensor for the measurement of instantaneous particle velocity in fluid flow is based on the principle of convective heat transfer. The rate of heat transfer and flow velocity \(v_0\) are related by the Kings formula

\[
Q = (A_1 + B_1 \sqrt{v_0}) * (T - T_0)
\]

This equation holds good, down to approximately 0.3 m/s for 55 P 11 hot wire probe used in the measurements.
The anemometer output is the bridge voltage \( v \) and the squared voltages \( v^2 \) and \( v_0^2 \) are linearly related to the heat loss of the wire at certain velocity and zero velocity respectively.

The calibration curve shown in Figure 44 was found non linear below the flow velocity of 30 f.p.s.

Mean flow velocity was measured indirectly by a pitot tube. The sensitivity and accuracy of inclined manometer is not good below a head of 1 mm H_2O corresponding to 4 m/s flow velocity. The hot wire probe on the other hand is particularly sensitive in this low velocity region due to the linear relationship between the probe heating power and the square root of velocity. The hot wire was therefore calibrated at higher (> 30 f.p.s.) velocity against a pitot tube and used directly as a flow velocity indicator in the very low speed range.

Due to this reason, calibration curve between the bridge output voltage squared and square root of flow velocity was replotted, as shown in Figure 45. The resultant straight line was extrapolated to the low velocity region. Extrapolation may be expected to show the true sensitivity characteristic down to a mean velocity of 0.3 m/sec. when working with D.I.S.A. 55 P 11 Probe.

The calibration curve was plotted using the calibration apparatus shown in Figure 38C.
Probe Technical Data (D.I.S.A. 55 P 11)

Sensor Dimensions = 5 µm dia. 1.25 mm long
Sensor Resistance $R_{20} = 4.54 \Omega$
Temperature Coefficient of resistance $\alpha_{20} = 0.36 \%/°C$
Max. sensor temperature = 300°C
Max. ambient temperature = 150°C
Minimum velocity = 0.2 m/s
Maximum velocity = 500 m/s
Frequency Limit $f_{cpo} = 400$ kHz
Probe overheating ratio = $\frac{R - R_0}{R_0} = 0.8$
Resistance Ratio = $\frac{R}{R_0} = 1.8$
$R$ (operating) = $4.54 \times 1.8 = 8.172 \Omega$
Probes current $= \frac{V_{DG}}{20 + R_c + R}$ = 0.122 A (at 12 f.p.s.)
$R_c = 0.046 \times 5 = 0.230 \Omega$

Figure 38C illustrates the D.I.S.A. 55 P 11 single sensor probe, probe-supports, mounting and the probe adapter.

D.I.S.A 55 M 01 Main Unit - Technical Data

A Max. upper frequency limit
A.1 H.F. filter setting = 2 Hz.
Frequency limit = 120 kHz.
A.2 Maximum output voltage swing, peak to peak
At +36 v. supply voltage under no load condition, and frequency < 10 kHz, voltage swing = 30 v.
A.3 Sensitivity during resistance measurements
Approximately 1% F.S.D./m.

A.4 Temperature drift
The total drift consists of equivalent contributions from input (ΔV_{IN}) and output drifts (ΔV_{out})
Equivalent input drift = ± 0.5 μV/°C
Equivalent output drift = ± 15 mV/°C

B Square Wave Generator
Frequency range = 3 kHz.
Rise time = 0.15 μsec.
Output signal during performance test = 0.5 v.
Square wave signal is applied at amplifier output to obtain a damped output with minimum oscillations.
Refer to Figure 38B for square wave response curve, obtained after coil compensation for the 55 M 01 unit.
Accuracy = 0.1%
Temperature coefficient is < 10 x 10^{-6}/°C

C Voltmeter
It is used for the measurement of internal and external voltages and for bridge balance indication
Ranges for internal voltages 30, 10*, 3, 1 v.
Range for external voltage 10 v.
Accuracy of measurement = 2% of F.S.D.

*Settings used

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Decade Resistance

Range = 0 - 99.99

(Setting = 8.17)

Physical Data

Ambient temperature range 0°C to 45°C

Dimensions (HWD) 106 x 212 x 296 mm.
Incl. 55 M 01 Power Pack

Shock - 70 g' 11 m/sec 3 axis non operating

Weight - 2.9 kg.

Power Supply

55 M 01 main unit is operated by 55 M 05 Power pack.

Supply voltage used = 16 to 36 v D.C. (+ve)

Drain on Positive Supply = 200 mA + bridge current
+ current consumed by plug in units.

Drain on negative supply = 130 mA max.

Technical data for type 55 M 10 C.T.A. standard bridge

Top resistance (R_t) = 50

Bridge Ratio = 1:20

Total Bridge Current I_B = 1.05 * I_p

= 1.05 *.12 = 0.126 A
(at 8.1 m/s)

Sensitivity:

V(out) = (R_p + R_t + R_c) * I_p

Sensor Current (I_p):

It depends on the probe resistance and voltage and is determined by the calibration curve.
Maximum obtainable probe power $= I_p^2 R_p = 4$ watt max.
Accuracy of resistance measurements $= \pm 0.25\%$
Operating current in resistance measurements $= 0.8$ ma
Probe cable length used $= 5$ m.
Max. upper frequency limit $= 200$ kHz approximately
Output noise $= (\text{for } 5\,\mu\text{m tungsten probe wire})$
$= 20\,\mu\text{V}_{\text{r.m.s.}}$ for $0.013\%$
turbulence levels ($10\,\text{m/s air vel.}$)
Amplifier setting - "shaped"
Output impedance - approximately $10\,\Omega$ (with normal feedback through bridge)
Ambient temperature range $= 0^\circ$ to $+45^\circ$C
D.I.S.A.-Type 55 D 31 Digital Voltmeter

This instrument is suitable for measuring D.C. voltages in the range ± 1 mv to ± 200 v. Using a dual scope principle it offers an accuracy of 0.1 percent of the measuring range ± 1 digit.

Time constant for the integrating circuit was chosen as 0.3 sec, giving the mean value of turbulence signal within the above range.

Technical Data

D.C. Voltage Range = ± 10 v.
Resolution = 1 mv.
Measuring time = 200 ms.
Input Impedence = 1 m.n.
Polarity Switching = Automatic with Readout
Input filter time constant = 0.3 sec
Temperature coefficient = 0.01%/°C for 25° ± 10°C
Power consumption = 0.8 VA

D.I.S.A. Type 55D-35 R.M.S. Voltmeter

It was used to indicate the true r.m.s. value of the fluctuating component of velocity and covers a wide dynamic range from 300 µv to 300 v.

It is capable of processing voltages with high crest factor (up to 5 at f.s.d. and up to 15 at 1/3 f.s.d.). This means it is capable of accurately indicating random signals as encountered in turbulence measurements.
Technical Data

Measuring range = 0.1 v.

Input Impedence = 1 mΩ//30 pf.

Frequency range = 0.1 Hz. to 700 kHz.

Lower frequency limit = 1 Hz.
(corresponds to integration time const. 0.3 setting)

Frequency response = 1 Hz. to 100 kHz. ± 1%

Crest factor = 10 at half scale deflection

R.M.S. output = +1 v for (f.s.d.)

(approx. 100 μV)

Accuracy of r.m.s. output = ± 1% of max. output

voltage down to -15 dB.

±2.5% of max. output

voltage from -15 dB to

-20 dB (at mid range

frequencies).

Meter Accuracy = 0.5% of f.s.d. in

(1 - 10 VRMS range)

Time Constant = 63% of final r.m.s. output

is reached at 50% of time

const. (i.e. 0.5 x 0.3

= 0.15 sec)

99% of final value is

reached at 67% of time

const (i.e. 0.201 sec.)

Permissible Ambient Temperature = 0 to 45°C
Measurement of Turbulence

Turbulence measurements are based upon the slope, \( \frac{dV}{dv_0} \) of the bridge D.C. voltage versus flow velocity curve expressed as volts/m/sec (refer Figure 45). The slope was calculated from this calibration curve at the flow velocity (mean) in question. The r.m.s. voltage for 1 percent turbulence is then given by

\[
V_{(r.m.s.)} = \frac{Mean\ flow\ velocity \times \frac{dV}{dv_0}(volts)}{100} \quad (I-A)
\]

and

\[
\text{Percentage of turbulence} = \frac{V_{r.m.s.} \times 100}{\frac{dV}{dv_0} \times \text{Mean Flow Velocity}} \quad (I-B)
\]

Typical values of Intensity of turbulence as obtained in the test section (in X-direction) are tabulated in Table I-T-3.
APPENDIX IB

AUDIO FREQUENCY 1/3 OCTAVE VOLTAGE
ANALYSIS OF AIR FLOW TURBULENCE SPECTRUM

General

The air flow turbulence signature recorded on the SE-84 tape recorder was played back through B&K audio frequency spectrometer type 2112 to B&K level recorder type 2305 so as to obtain a noise spectrogram of turbulent pressure fluctuations. The octave band pressure levels were converted to fluctuating velocity components ($\delta v_n$) using the probe calibration curve, which were then used to calculate $\int \rho v_0 \delta v_n$ value, giving the pseudo sound level.

Measuring Arrangement

Figure 68 illustrates the measuring arrangement employed for automatic recording of voltage analysis. Complete synchronisation between audio frequency spectrometer and the level recorder was achieved using the remote control socket and cable AQ-0002.

Recording of Spectrogram

1. Calibration of Spectrometer (B&K 2112)

The control knobs on front pannel were set as follows:

- Input switch - "Direct"
- Meter range - "Ref"
- Meter switch - r.m.s. fast
- Range multiplier - X1, 0 dB
- Function selector - Linear 2-40,000 c/s
Amplifier Input Sensitivity potentiometer adjustments made as necessary.

2. **Calibration of Level Recorder '2305'**

Logarithmic Potentiometer used - 50 dB.

Controls set as follows:

- **Rectifier Response** - r.m.s.
- **Potentiometer range** - 50 dB.
- **Lower limiting frequency** - 20 Hz.
- **Writing speed** - 1000 mm/sec.

(used only for calibration during synchronisation procedure to give an unambiguous indication of filter switching point. Later moved to 315 mm/s. for recording purposes.)

Paper drive - stop and forward

Single chart continuous recording - in upper position

Input attenuator - 10

Input potentiometer - Set to indicate f.s.d. - 4 dB i.e. 46 dB on frequency calibrated paper.

**Adjustment of Single Chart Automatic Stop**

Frequency calibrated paper QP 1123 was inserted into level recorder and paper speed set to 10 mm/sec.

Gear lever on level recorder was pulled out to commence single chart continuous recording of spectrogram.
Synchronisation Between Level Recorder and Spectrometer

The filter switching on the spectrometer is synchronised with the paper movement by setting the following:

- Screws (refer instruments manual) turned until marking cut in the screw was in its upper position.

Spectrometer controls were set as follows:

- Function selector - 1/3 octave 0 dB.
- Automatic switching - off.
- Filter switch - One step counterclockwise position w.r.t. 12.5 Hz. position.
- Automatic switching - on.

The controls on level recorder were set as follows:

- Paper drive - stop.
- Single chart continuous recording push button pushed in till the paper moves to about 200 Hz. line.

The correct synchronisation was achieved within the proper 1/3 octave filter when the component of power supply fundamental frequency (60 Hz) was represented as the highest value on the spectrogram within the filter covering this fundamental.

Adjustment to the Turbulence Voltage Signal

The following settings were made on spectrometer and level recorder:

- Rectifier response - r.m.s.
- Lower limiting frequency - 20 Hz.
- Writing speed - 315 mm/s.
- Paper speed - 10 mm/s.
By choosing this combination of L.L.F. and writing speed, very stable operating conditions were achieved with no appreciable overswing of level recorder.

Function selector - Linear 2-40,000 c/s
Meter range - -40 dB
Range multiplier - X1, 0 dB
Meter switch - r.m.s. - fast

Recording of Spectrogram

The function selector was switched to 1/3 octave, 0 dB position and single chart continuous recording pushbutton actuated to commence the recording. Figure 40 shows the turbulence spectrograms at 12 f.p.s. flow velocity at the test section.
APPENDIX II

PRESSURE PROBE MICROPHONE FREQUENCY RESPONSE
MEASUREMENT AND CALIBRATION

General
The B&K half inch condenser microphone 4134 has a flat pressure response up to 20 kHz (± 2 dB) and meets the ANSI-S1.12-1967 standard for type I laboratory standard microphones.

When used with Field Effect Transistor Preamplifier (F.E.T.), B&K 2619 it produces an effective lower limiting frequency of 5 Hz (-3 dB). Since we were not interested in pressure response measurements at very low frequencies, this was suitable enough for our fluctuating pressure measurements.

The pressure response of a microphone is defined as

\[ M_p = \frac{v_0'}{p_1} \]

where \( v_0' \) is r.m.s. output voltage and \( p_1 \) is the r.m.s. value of sound pressure exerted on the diaphragm.

Since the microphone body dimensions are not negligible as compared to incident wavelength, reflection and refraction of sound waves due to microphone body was expected to disturb the local sound field; thereby increasing pressure on the diaphragm and hence increasing the output voltage. This effect is particularly noticeable when taking measurements inside the ear and closed cavity where the free field conditions no longer apply and the microphone volume is comparable to
the coupler volume.

The microphone 4134 was therefore used with a probe tube (with suitable damping, to avoid resonance amplitude fluctuations) and a reasonably linear frequency response was obtained (within ± 2.5 up to 2000 Hz) as shown in Figure 64.

**Probe Microphone Kit - B&K Type UA-0040**

Since the performance of the probe microphone depends on the length and width of the tube, the acoustical impedance of the microphone cartridge (equivalent volume of the 4134 cartridge = 0.010 cm³ up to 3 kHz), and the volume between the microphone diaphragm and the end of tube terminating this volume; various tube length and diameters were tested for frequency response and finally a tube 4 mm O.D. and 240 mm long was found to be most satisfactory for the measurements. The tube diameter should be very small compared to the wavelengths and the length be comparable or greater than the wavelength for a wide range of audio frequency.

Resonance appeared when the length of tube was an odd multiple of \( \frac{\lambda}{4} \) i.e. \((2n + 1)\frac{\lambda}{4}\) where \( n \) is an integer and \( \lambda \), the wave length, as shown in Figure 64. This was caused by the low input impedance of the probe tube.

By using a suitable amount of damping material at the far end of the probe tube it was found possible to damp amplitude undulations both at low and high frequency end of response curve while some undamped oscillations still show up over about 500 Hz, as seen in Figure 64.
Equipment Set Up for Calibration and Damping Adjustment

The arrangement of equipment suitable for recording the frequency response of microphone with the probe tube fitted is shown in Figure 38A. It employs a beat frequency oscillator type B&K 1022, two measuring amplifiers 2607 (with SA 0057 measuring scales), the level recorder 2307 and the coupler and sound source (earphone) supplied with probe kit UA 0040. This system is suitable for a frequency range up to 5 kHz. The signal from the regulating microphone (4133) is fed back to the compressor circuit of the oscillator, which regulates to a constant sound pressure level in the coupler. The level recorder plots the output voltage for a constant sound pressure level input to the microphone. A mechanical drive between the level recorder and the oscillator ensures frequency synchronism. B&K pressure microphone manual shows a sectional drawing of the coupler with the probe tube and sound source in position, as used in this study.

Since the acoustic impedance of the probe microphone was found to be greater than the acoustic impedance of 2 cm.³ coupler, used for calibration, the calibration results were valid for use of probe microphone in free field conditions.

It was found that by using the Teflon gasket under the probe adapter, the microphone pressure equaliser hole could be blocked and microphone equivalent volume reduced to about 0.02 cm³; yielding greater linearity in frequency response of probe. But now the probe was found to respond
to static pressure as well, which was not desired; since it was required to measure fluctuating pressure components only. Therefore the pressure equalisation hole should not be blocked when making measurements under dynamic flow conditions, which would otherwise yield higher S.P.L.
APPENDIX III

EXPRESSION FOR PRESSURE FLUCTUATION OF TURBULENCE

In a steady flow the pressure fluctuations caused by turbulence are assumed to propagate with the velocity of airflow while those due to aerodynamically generated sound propagate with the velocity of sound in the medium.

Under the following assumptions an expression for pressure fluctuations due to turbulence can be derived.
1. Turbulence intensity for flow is < 4% for overall measurements; and maybe neglected w.r.t. main flow velocity.
2. Mean flow velocity is < 10 m/s
3. When compared with the level of pressure fluctuations due to turbulence, the S.P.L. is negligible.
4. The direction of main flow velocity is invariant with time.

\[ v = v_0 + \delta v_n \]
If a velocity fluctuation \( \delta v_n \) exist in the flow tube of the main flow velocity \( v_0 \), the resultant velocity \( v \) is expressed by \( (v_0 + \delta v_n) \) as shown in the figure. If \( |v_0| \gg |\delta v_n| \) then \( v \approx v_0 \) and the quasi-stationary condition in the flow tube should be established. The following expression is given for the fluid in the stationary flow tube.

\[
\frac{1}{2}v^2 + p + \int \frac{dp}{\rho} = \text{Const}
\]

(1)

where \( \rho \) and \( p \) are fluid density and pressure respectively and \( V_p \) is the potential in the flow tube. Assuming the fluid is incompressible at very low velocity, the flow velocity \( v_0 \) varies by a small amount \( \delta v_n \) perpendicular to the direction of the mean flow under the conditions of Equation (1). Then

\[
v = v_0 + \delta v = v_0 + \sum_n (\delta v_n) \sin n \omega t
\]

(2)

and

\[
\int \frac{dp}{\rho} = \frac{p}{\rho} = \frac{p_0 + \delta p}{\rho} = \left[ \left( \frac{p_0}{\rho} + \sum_n (\delta p_n) \right) \right] / \rho
\]

(3)

where \( \omega n \) is the \( n \)th component of angular frequency of fluctuations. By substituting Equation (2) and (3) into (1) the following expression is obtained.

\[
\frac{-\delta p_n}{\rho} = v_0 \delta v_n \sin n \omega t \left[ 1 + \frac{1}{2} \sum_n \frac{\delta v_n}{v_0} \sin n \omega t \right]
\]

where \( \frac{1}{2}v_0^2 + p + \frac{p_0}{\rho} = \text{constt} \).

Under the conditions of \( \delta v_n \ll v_0 \) the r.m.s. of \( \delta p_n \) is

\[
p_1 = (\delta p_n)_{r.m.s.} = \rho v_0 (\delta v_n) / \sqrt{2}
\]

\[
p_1 = (\delta p_n)_{r.m.s.} = \rho v_0 (\delta v_n)_{r.m.s.}
\]
Thus if the mean flow velocity and the velocity fluctuations are measured independently at a point in the flow, the pressure fluctuations could be determined by the product of both values.
EVALUATION OF EQUIVALENT CONTINUOUS SOUND PRESSURE LEVEL ($L_{eq}$) AND NOISE DOSE

For comparison purposes it was necessary to convert a statistically time varying random noise signal to an equivalent continuous level for the duration of acoustical measurements. It could be obtained as follows.

The general expression for $L_{eq}$ is given as

$$L_{eq} = 10 \log_{10} \left[ \frac{1}{T} \int_{0}^{T} \left( \frac{p(t)}{p_0} \right)^2 \, dt \right]$$  \hspace{1cm} 4(a)

where $p_0 = 2 \times 10^{-5} \, \text{N/m}^2$ = reference pressure

now $S.P.L. = 10 \log_{10} \left( \frac{p(t)}{p_0} \right)^2$

or $\left( \frac{p(t)}{p_0} \right)^2 = 10 \left( \frac{S.P.L.}{10} \right)$

Substituting this value of pressure ratio squared in Equation 4(a) we have

$$L_{eq} = 10 \log_{10} \left[ \frac{1}{T} \int_{0}^{T} \left( 10 \frac{S.P.L.}{10} \right) \, dt \right]$$

or $$L_{eq} = 10 \log_{10} \frac{1}{T} \sum_{i=1}^{n} \left( 10 \frac{S.P.L.}{10} \right) \times t_i$$  \hspace{1cm} 4(b)

Noise dose is given as:

$$N.D. \quad \text{OSHA/ISO} = \sum_{i=1}^{n} \frac{C_i}{T_i} \times 100$$  \hspace{1cm} 4(c)

where $C_i =$ Actual time at each sound pressure level

$T_i =$ Maximum time allowable as per OSHA or I.S.O.
standard at that level.

$$T_{i\text{OSHA}} = 8 \left(\frac{L_i - 90}{5}\right)$$

and

$$T_{i\text{I.S.O.}} = 8 \left(\frac{L_i - 80}{3}\right)$$

Equations 4 - b, c, d and e have been incorporated in a basic program to compute "L\text{eq}" and noise dose from the statistical noise data. Alternatively noise dose can be computed by a noise dose meter which uses the following relationship

$$N.D._{\text{OSHA}} = 100 \int_0^{T/8} \left(\frac{p(t)}{0.632}\right)^{1.2} dt$$

where T is the duration of measurement in hours and p(t) is the time varying sound pressure. Using a nomogram, a 'L\text{eq}' value could be obtained from the percentage noise dose.
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3. DISA Instrumentation and Service Manual for Type 55 D 31 Digital Voltmeter.
5. Hot Wire and Hot Film Anemometry - An Introduction to the Theory and Application of DISA Constant Temperature Anemometer - by C. G. Ramussen and B.B. Madsen.
6. Instruction and Service Manual for DISA Type 55 D 05 Constant Temperature Anemometer.
9.A Low speed wind tunnel testing- Pope A. and Harper J.J.
11. Experimental Fluid Mechanics - Bradshaw, P.

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19. R. Harrison. "Do Motorcycle Helmets Make Good Hearing Protectors".


22. Transformation of Sound Pressure Level from the Free Field to the Ear Drum in Horizontal Plane". E.A.G. Shaw - Division of Physics, N.R.C. Ottawa, Ontario KIA OS1.


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TABLE I-T-1

H. W. Probe Calibration Data

D.I.S.A. miniature hot wire probe 55 P 11
Pilot tube # PBA-24-F-22 KL

\[
\begin{align*}
R_0 &= 3.76 \\ 
R &= 1.8 \times 3.76 = 6.72 \\ 
\alpha &= 0.8 \\ 
I_p(\text{max}) &= 0.179 \text{ amp} \\ 
V_0 &= 2.84 \text{ v} \\ 
\text{Nozzle dia.} &= 1" \\ 
\text{Slope} &= 0.0112
\end{align*}
\]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>manometer head (mm)</th>
<th>Flow Velocity (v) (fps)</th>
<th>Bridge Output Voltage (V_{\text{D.C.}}) (volt)</th>
<th>(V_0^{\text{r.m.s.}}) (m.v.)</th>
<th>(V_0^{\text{D.C.}}) Volt</th>
<th>(v^{\frac{1}{2}}) f.p.s.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
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</table>
### TABLE I-T-2

**H. W. Probe Calibration Data**

D.I.S.A. miniature hot wire probe 55 P 11
Pilot tube # PBA-24-F-22-KL

\[
\begin{align*}
R_0 &= 4.54 \\
R &= 8.172 \\
V_0 &= 2.68 \text{ V.}
\end{align*}
\]

Flow Velocity = 12 f.p.s. (with plugged fan intake)
Nozzle Dia. = \(1''\)

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Manometer Head (mm)</th>
<th>Flow Velocity (v)</th>
<th>Bridge Output Voltage</th>
<th>(V_0) r.m.s. (m.v.)</th>
<th>(V_0^2) D.C. Volt</th>
<th>(v^2) (fps)</th>
</tr>
</thead>
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<td>0</td>
<td>2.69</td>
<td>0</td>
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<td>5</td>
<td>26.94</td>
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<td>38.10</td>
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<td>46.66</td>
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<td>22.56</td>
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</table>
**TABLE I-T-3**

Wind Tunnel Turbulence Data

(C. T. Hot Wire Anemometer Measurements)

\[ V_0 = 2.84 \text{ volt} \]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>V(_{\text{D.C.}}) (volt)</th>
<th>V(_{\text{r.m.s.}}) (mv)</th>
<th>Wind Speed (f.p.s.)</th>
<th>I.T. Intensity of Turbulence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.37</td>
<td>72</td>
<td>47.0</td>
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<td>1.64</td>
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<td>1.69</td>
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<td>1.68</td>
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<td>80</td>
<td>84.5</td>
<td>1.68</td>
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</table>
TABLE I-T-4

Constant Temperature Anemometer Measurement of Turbulence Scale at Helmet Surface

Flow Velocity = 90 f.p.s.

<table>
<thead>
<tr>
<th>Probe Position</th>
<th>Distance from Surface</th>
<th>$V_{D.C.}$ (volts)</th>
<th>$V'_{r.m.s.}$ (volts)</th>
<th>I.T. (%)</th>
</tr>
</thead>
<tbody>
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<td>0.260</td>
<td>6.60</td>
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<td>1.0&quot;</td>
<td>4.18</td>
<td>0.320</td>
<td>6.60</td>
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<tr>
<td>I</td>
<td>1.5&quot;</td>
<td>4.50</td>
<td>0.210</td>
<td>4.60</td>
</tr>
<tr>
<td>I</td>
<td>2.0&quot;</td>
<td>4.58</td>
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<td>1.90</td>
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<tr>
<td>II</td>
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<td>0.110</td>
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<tr>
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<td>1.00</td>
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<tr>
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<td>1.5&quot;</td>
<td>4.84</td>
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<td>0.93</td>
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I will run times inputs

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Let $Y = 0$

Let $N = 10$

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Let $Y = Y + 1$

Let $X = X + 1$

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Let $X = X + 1$

Let $Y = Y + 1$

Let $X = X + 1$
AVERAGE S.P.L.'S IN ACOUSTIC PLENUM BEFORE THE ADDITION OF CONVERGENT AND TEST SECTION. Flow Vel: 40 f.p.s.

![Graph showing sound pressure level (S.P.L.) in an acoustic plenum before the addition of convergent and test section. Flow velocity: 40 f.p.s.](image)
Fig 1A1. DAMAGE RISK CONTOURS FOR ONE EXPOSURE PER DAY TO FULL OCTAVE AND 1/3 OCTAVE BANDS OF NOISE. THIS GRAPH MAY BE APPLIED TO THE INDIVIDUAL BAND LEVELS PRESENT IN BROAD -BAND NOISE.

Fig 1A2. TOTAL DURATION OF A NOISE ALLOWABLE DURING AN 8 HOUR DAY AS A FUNCTION OF NUMBER OF PERIODIC INTERRUPTIONS. AN EXPOSURE CYCLE IS COMPLETED EACH TIME THE dBA. S.P.L. DECREASE TO OR BELOW 89 dB.
CONSTRUCTION DETAILS OF THE TEST SECTION.

CONTRACTION SECTION

TEST SECTION

Fig: 4
NOISE SPECTRUM INSIDE THE BLOWER HOUSING AT DIFFERENT FLOW SPEEDS.

WITH PROBE TUBE FITTED MICROPHONE B&K 4134.

FREQUENCY - Hz

SOUND PRESSURE LEVEL - dB

104  124  144

91 FPPS
20 FPPS
2 K
SPECTRUM OUTSIDE CANVAS COUPLING

FREQUENCY

SPL - DBA

50

0

K

FIG. 6
VIBRATION LEVELS ON COUPLING - BEFORE RE-ENFORCEMENT

Amplitude (G)

Frequency (Hz)

225 Hz cut off

0.316 G

FIG. 7
vibration levels on flexible coupling - after re-enforcement
amplitude

vibration levels on top of blower

frequency in Hz

amplitude in g

2K

PTG 9

FIG 19
vibration levels on expansion section
vibration levels at test section

amplitude

FREQUENCY - Hz

FIG. 12
vibration levels at inlet acoustic chamber

amplitude

FREQUENCY - Hz

FIG: 13
OVERALL EFFECT OF MODIFICATIONS

- 92 dBa ▲ before modification
- 72 dBa • after modification

OCTAVE BAND CENTRE FREQ.- Hz.

Fig. 14-A
DYNAMIC RESPONSE OF EAR-BUG WITH DIFFERENT ATTENUATION CIRCUITS.

IMPEDENCE MATCHING CIRCUIT LAYOUT.

(I) MIC. 3.9K

(II) MIC. 5.1K

LINEAR RANGE: CODE:

<table>
<thead>
<tr>
<th>Output S.P.L. (dBA)</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>85-110</td>
<td>CURVE-I RED PLUGS 008</td>
</tr>
<tr>
<td>70-95</td>
<td>CURVE-II RED PLUGS 009</td>
</tr>
<tr>
<td>75-100</td>
<td>CURVE-III BLUE PLUGS 003 005 &amp; 006</td>
</tr>
<tr>
<td>85-115</td>
<td>CURVE-IV BLACK PLUGS 112 &amp; 113</td>
</tr>
</tbody>
</table>

INPUT SOUND PRESSURE LEVEL (dBA) FIG: 16
COMPARISON OF EAR-BUG MK.3-300 RESPONSE (AFTER SHAPING) WITH A.N.S.I. TYPE II TOLERANCE LIMITS RECOMMENDED FOR PRECISION S.L.M.

RELATIVE SOUND PRESSURE LEVEL(dBA.

FREQUENCY: Hz.

FIG: 18
DIRECTIONAL RESPONSE OF EAR-BUG
REF. SIGNAL = 90 dBA AT 1000 Hz.
Rec. MK. 3-300 AND RED ATTENUATOR #111
DISTANCE OF MIC. FROM SPEAKER = 1.5 M
REFERENCE SPL. 90 dBA

DIRECTIONAL RESPONSE OF EAR-BUG MICROPHONE.
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EQUIPMENT LAYOUT FOR THE STUDY OF TUNNEL END REFLECTION EFFECTS.

FIG: 22.
THIRD OCTAVE BAND PRESSURE LEVELS AT INTAKE END OF BLOWER AT DIFFERENT SPEED.

- 91FPS.
- 86FPS.
- 81FPS.
- 76FPS.
- 66FPS.
- 50FPS.
- 12FPS.

THIRD OCTAVE BAND CENTRE FREQUENCY (Hz)
wind noise in empty test section
OCTAVE ANALYSIS OF WIND TUNNEL NOISE

- A: WITHOUT SCREEN
- B: WITH WIND SCREEN
- C: WIND SCREEN

WIND SPEED: 12 F.P.S.
R.T.: 71°F.

TURBULANCE LEVEL

frequency - HZ.

s.p.l. (db)

FIG. 26
THIRD OCTAVE ANALYSIS OF TURBULENCE SIGNATURE AT 12 FPS.
MEASURED IN EMPTY TEST SECTION.

FIG: 27
FREQUENCY SPECTRUM OF NOISE AT TEST SECTION: FLOW VELOCITY = 12FPS.
MIC. B&K 4134 WITH PROBE TUBE.
THIRD OCTAVE SPECTRUM OF NOISE AND TURBULANCE IN WIND TUNNEL
MEASURED 5FT UPSTREAM OF MODEL AT 91 FPS FLOW VELOCITY AT THE TUNNEL AXIX.

PROBE MIC WITHOUT WIND SCREEN AND TUBE.

θ = 0°

θ = 90°

WITHIN WALL BOUNDARY LAYER
(4134+grid.)

BACKGROUND NOISE LEVEL.

S.P.L. 90
250
500
1000
2000
4000
Hz.

OVERALL dBA.
31.5
63
125
250
500
K
2K
4K
FIG: 29
THIRD OCTAVE ANALYSIS OF TURBULENCE SIGNAL.

FIG. 30
FREQUENCY RESPONSE OF PRESSURE MICROPHONE B & 4134 AND GRID WITH AND WITHOUT THE NOSE CONE

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NOS. OF ENSEMBLES = 32

OVERALL SPL.

4134 with nose cone = 103.3 dBA. ——— (A)
4134 only = 112.5 dBA ——— (B)

COMPARISON OF NOISE MEASURED 5 FT. UPSTREAM OF MODEL
WITH AND WITHOUT NOSE CONE AT (91 FPS.) FLOW VELOCITY.

FIG: 32
NOS. OF ENSEMBLES = 32

OVERALL S.P.L.
MIC(4134+grid) WITHIN TUNNEL WALL = 73.2 dBA. ----(A)
MIC(4134+grid+nose cove) AT THE TUNNEL AXIX, 5FT. UPSTREAM = 74.5 dBA. ----(B)

N.B. ANALYSIS OF WIND NOISE MEASURED 5FT. UPSTREAM OF MODEL

AT THE WIND TUNNEL AXIX AT 19 FPS. FLOW VELOCITY.
N.B. ANALYSIS OF NOISE MEASURED WITHIN TUNNEL WALL, 5 FT. UPSTREAM OF MODEL, SHOWING THE EFFECT OF CHANGE IN FLOW SPEED.

(MICROPHONE USED: B&K 4134 WITH GRID.)
N.B. ANALYSIS OF NOISE 5 FT. UPSTREAM OF MODEL MEASURED WITH A NOSE CONE PROTECTED MIC. AT DIFFERENT FLOW SPEEDS.

NOS. OF ENSEMBLES = 32

OVERALL SPL.

\[ \text{OVERALL SPL.} = \frac{74.5 \text{ dBA}}{74.5} = 103.3 \text{ dBA} \]

FREQUENCY - Hz

Sound Pressure Level - dB

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NOISE SPECTRUM MEASURED IN THE TEST SECTION WALL WITH AND WITHOUT THE MODEL OPERATING IN TEST SECTION.

FLOW VELOCITY: 91 FPS.

WITH MODEL

WITHOUT MODEL

SOUND PRESSURE LEVEL, dBA.

OVERALL 31.5 63 125 250 500 1k 2k 4k

OCTAVE BAND CENTRE FREQUENCY (Hz.)

FIG: 36
noise spectrum outside helmet (r)

at 90 fps.

(X=0.5"; PROBE TUBE PTTED MIC. B&R 4134;
HELMET AND VISOR; POSITION: Rt. EAR.)
FIG. 38-A (PROBE FREQUENCY RESPONSE SETUP.)

PROBE TUBE

FIG. 38-A

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TURBULANCE MEASUREMENT SETUP.

DAMPED SQUAREWAVE RESPONSE CHARACTERISTIC OF HOT WIRE ANEMOMETER.

FIG. 38-B
HOT WIRE PROBE CALIBRATION WITH PITOT TUBE.

FIG: 38-C
FLOW PATTERN AROUND THE HELMET AT 90 FPS: FLOW VELOCITY

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POSITION OF MICROPHONES IN THE SUBJECTS CAVUM

NOISE DOSE MIC.

EAR-BUG MIC.

FIG:38-F
SHAPE OF THE TWO PINNA TESTED

FIG. 38-G

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REAL TIME ANALYSER AND AVERAGER

FIG: 38-I
PROBE POSITION # 1.

FLOW TURBULENCE SPECTRUM OUTSIDE THE HELMET AT TEST SECTION.

FLOW VELOCITY 91 FPS.

FIG. 39
1/3 OCTAVE TURBULENCE SPECTROGRAM AT 12 FPS.
MEASURED 5FT. UPSTREAM OF TEST SECTION.

METER RANGE = -60 dB
RANGE MULTIPLIER = 0 dB.
FUNCTION SELECTOR = 0 dB.
X-VELOCITY COMPONENT.

FIG: 40
FLOW TURBULENCE SPECTRUM OUTSIDE THE HELMET AT TEST SECTION.

For Probe Position #2.

FLOW VEL: 91 F.P.S.

1/2 inch

1 inch

1.5 inch

FREQUENCY - Hz

FIG: 41.
N.B. ANALYSIS OF A-WEIGHTED NOISE FROM EAR BUG MEASURED IN WIND TUNNEL AT (91FPS.) MANNEQUIN WEARING HELMET AND VISOR.
NARROW BAND ANALYSIS OF A-WEIGHTED NOISE AT SUBJECTS EAR;
MEASURED AT 50 MPH. WITH EAR BUG, HELMET AND VISOR.
MOTORCYCLE: HONDA-750-FOUR, COUNTRY RUN. (TAPE #30.)

FIG. 43
DISA type - 55A25 hot wire probe calibration curve

- $t = 27^\circ C$
- $p = 760\text{ mm Hg}$
- $R_c = 3.76\,\Omega$
- $R_0 = 6.77\,\Omega$
- $V_0 = 2.84\,V_{\text{d.c.}}$

flow velocity - f.p.s.
extrapolated calibration curve for probe 55 PI

\[ T_0 = 72^\circ F \]
\[ p = 760 \text{ m.m. Hg.} \]
\[ R_0 = 4.54 \Omega \]
\[ R = 8.11 \Omega \]
\[ V_0 = 2.68 V_{dc} \]

**Figure 45.**
FREQUENCY SPECTRUM AT 6" FROM A POINT SOURCE: COMPARISON BETWEEN FREE FIELD AND WIND TUNNEL MEASUREMENTS.

WHITE NOISE SOURCE: 20KHz.

FIG. 47

FREE FIELD

TEST SECTION
directivity effect of flow noise at RT. ear position with small helmet.

FIG. 48-A
AZIMUTH DEPENDENCE OF S.P.L. AT RT.-EAR

- PLAIN VISOR
- CURVED VISOR
46 F.P.S. HELMET(S)
DIRECTIONAL EFFECT ON NOISE INCIDENT UPON L- AND R- EARS

FLOW VEL: 100 FPS

HELMET(S) & VISOR

AZIMUTH DEPENDENCE OF S.P.L. AT EARS

FIG: 50
EFFECT OF FORWARD INCLINATION ON NOISE FIELD MEASURED AT R.-EAR POSITION:
MANNEQUIN WEARING HELMET AND PLAIN VISOR.
FLOW VELOCITY=90 F.P.S.
NOISE HISTOGRAM FOR KAWASAKI-500 cc. HIGHWAY RUN AT 55 MPH.

AT EAR NOISE MEASUREMENT.
RIDER WEARING HELMET & VISOR

(WITH VISOR) $L_{eq} = 98$ dBA.  "$L_{eq} = 100$ dBA (WITHOUT VISOR)

N.D. (O.S.H.A.) = 362%

FIG: 53
NOISE HISTOGRAM FOR SUZUKI-380 cc. HIGHWAY RUN AT 55 MPH.

AT EAR NOISE MEASUREMENT WITH HELMET & VISOR.

N.D. (O.S.H.A.) = 382%

\[ L_{eq} = 100 \text{ dBA} \]
CASETTE TAPE # 11  Bruel & Kjaer

EAR BUG AT THE CAVUM OF THE CONCHA POSITION.

POSITION #1  POSITION # 2  POSITION # 3

110dB

100 dB

90 dB

FIG: 56-A

*D is depth from pinna outer flange to ear canal opening.

EAR #1

3.55 cm

EAR #2

3.3 cm

FIG: 56-B

PRESSURE DISTRIBUTION MEASURED AT ABOVE LOCATIONS

HARD WALL TUBE (EAR CANAL)

(EAR DRUM)

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EFFECT OF PINNA GEOMETRY ON SPL. AT E.C.O. POS.

120 dBA
EAR BUG AT EAR CANAL OPENING POSITION.

110 dBA

100 dBA

10 dBA

FIG. 57

FLOW HEAD = 57 MM.

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EQUIPMENT LAYOUT FOR FREQUENCY RESPONSE MEASUREMENTS.

Mannequin

20 kHz White Noise Field

Pressure Probe Microphone (B&K Model 4134)

From Earbug Microphone

Attenuator

Measuring Amplifier B&K Model 2607

Feedback to Compressor

Ear Bug Recorder Sony TC-51

Fig 58
EFFECT OF BLOCKAGE OF EAR CANAL.

RATIO OF S.P. AT MEATUS OPENING TO PRESSURE IN FREE FIELD AT CENTRE HEAD POSITION.

SOURCE DISTANCE:
R=46 CM.
E.CANAL LENGTH:
L=2.3 CM
E.C.SECCTIONAL AREA:
A=0.38 CM²
E.C.TERMINAL IMPEDANCE:
R"< oo A (C.G.S.- ACOUSTIC OHMS.)

E.A.G. Shaw & Téranishi

FIG. 59-A

R=8CM.
L=2CM.
A=0.4 CM²
R=oo A
POINT NOISE SOURCE.

RESPONSE OF REPLICA AT NORMAL INCIDENCE WITH HARD WALL EAR DRUM VS. FREQUENCY.

FREQUENCY: KHz.

FIG. 59 & FIG. 59-A
PRESSURE TRANSFORMATION FROM FREE FIELD TO EAR DRUM_MEASURED AT R.—EAR.

RESULTS OF SHAW

RESULTS OF WEINER

\[\Theta = 0^\circ\]
\[X = 46 \text{ cm.}\]

FIG: 60
RATIO OF SOUND PRESSURE AT EAR DRUM TO PRESSURE AT ENTRANCE TO EAR CANAL.

- SHAW'S RESULTS
- OUR RESULTS
- FRANCIS WEINER'S RESULTS

![Graph showing the ratio of sound pressure at the ear drum to pressure at the entrance to the ear canal across different frequencies.](image)

**FIG. 61**
WIND GENERATED NOISE LEVELS AT CAVUM AND E.C.O.
(WITHOUT HELMET.)

○ S.P.L.S AT E.C.O. WITHOUT PINNA.

CAVUM

EACH CANAL OPENING.

WIND SPEED-F.P.S.

FIG:62
WIND GENERATED NOISE LEVELS AT CAVUN AND E.C.O.
(WITH T.N.T.LARGE SIZE HELMET.)

S.P.L.S WITHOUT PINNA
(FROM FIG:48)

CAVUM
EAR CANAL OPENING.

WIND SPEED_F.P.S.

FIG:63
PROBE FREQUENCY RESPONSE.

FIG: 64.
FIG. 65-A AERODYNAMICALLY GENERATED SPL. MEASURED AT THE EAR WITH A BARE HEAD.

FIG. 65-B AERODYNAMICALLY GENERATED SPL. MEASURED AT THE EAR WITH A HELMET.
### TABLE - 66

**Constant Speed (50 mph) Motor Cycle Runs On Highway - Rider Wearing (T.N.T) Helmet Only**

(S.P.L. measured at R. ear cawum with ear bug only)

<table>
<thead>
<tr>
<th>Rider</th>
<th>S.P.L. (dBA)</th>
<th>Mean (m)</th>
<th>Standard Deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-3</td>
<td>M-4</td>
<td>M-5</td>
</tr>
<tr>
<td>A</td>
<td>96</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>93</td>
<td>94</td>
<td>95.5</td>
</tr>
<tr>
<td></td>
<td>92.5</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>C</td>
<td>92.5</td>
<td>93</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>92.5</td>
<td>92</td>
<td>91.5</td>
</tr>
<tr>
<td>D</td>
<td>89</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>91</td>
<td>92</td>
</tr>
</tbody>
</table>
### TABLE - 67

Constant Speed Motorcycle Runs - Rider Wearing T.N.T. Helmet Only

<table>
<thead>
<tr>
<th>Gear (f.p.s.)</th>
<th>Velocity</th>
<th>Rider</th>
<th>Motorcycle Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 Kawasaki 200 c.c.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Sound Pressure Levels in dBA)</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>A</td>
<td>77.0</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td></td>
<td>80.0</td>
</tr>
<tr>
<td>4</td>
<td>59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>73</td>
<td></td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>94.0</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>B</td>
<td>78.5</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td></td>
<td>83.5</td>
</tr>
<tr>
<td>4</td>
<td>59</td>
<td></td>
<td>82.0</td>
</tr>
<tr>
<td>5</td>
<td>74</td>
<td></td>
<td>91.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>98.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>93.0</td>
</tr>
</tbody>
</table>
STATISTICAL DISTRIBUTION OF SUBJECTIVE L' DATA FROM TABLE 66 AND 67.

MEAN (μ) = 93.811

STANDARD DEVIATION (σ) = 2.455

\[ z = \frac{x - \mu}{\sigma} \]

\[ \Phi \left( \frac{1}{\sigma} \sqrt{2 \pi} \right) \]

-68.27% 95.45% 99.7%
INSTRUMENTATION FOR FREQUENCY ANALYSIS OF TURBULENCE SIGNAL.

S-E EIGHT FOUR TAPE RECORDER

B&K AUDIO FREQUENCY SPECTROMETER

B&K LEVEL RECORDER

FIG: 68
VITA AUCTORIS


Obtained the Bachelor of Science degree in Mechanical Engineering from Agra University in 1970.

From 1970 to 1974 he worked as a quality control engineer with Escorts Motor Company in India, at their Motor Scooter Division.

From 1974 to 1975, he worked for Sinteris Canada Ltd. as quality control engineer in their powder metal plant at Blenheim, Ontario.

Currently a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor, Ontario, Canada.