NOISE RESEARCH IN CANADA:
PHYSICAL AND BIO-ACOUSTIC

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Summary—Canadian research on flow noise and various aspects of the aircraft noise problem is described. Establishments that have made contributions include the Defence Research Board, National Research Council, University of Toronto Institute of Aerophysics, A. V. Roe (Canada) Ltd. and Trans-Canada Air Lines.

Specific experimental and/or theoretical investigations related to the physical aspects of the problem include: aeolian tones; boundary layer noise (rigid wall and flexible wall); effects of boundary layers and noise on aircraft structures; distribution of noise sources along a jet; ground run-up mufflers; transmission of sound from, and acoustic energy flow in, a moving medium; sound generated by interaction of a vortex with a shock wave.

Specific investigations related to the bio-acoustics aspect of the problem include: surveys of noise in and outside aircraft; noise generated on air bases; the effects of noise on hearing; hearing conservation programmes; noise protection criteria; and the effects of hyperventilation on speech and hearing. In addition results are given of voice communication which include (1) spelling alphabets, (2) two-, three-, and four-digit sequences, (3) colour phrases, (4) radiotelephony distress signals Mayday and S.O.S. and (5) the effects of visual cues on the intelligibility of speech.

INTRODUCTION

This paper describes fundamental and applied research that has been conducted in Canada during the last few years on flow noise, and on various aspects of the aircraft noise problem. The work has been carried out by a number of people, and in a number of organizations. Principal among the latter are the Defence Research Board of Canada, the National Research Council, the University of Toronto Institute of Aerophysics, A. V. Roe (Canada) Ltd., and Trans-Canada Air Lines. Financial support for the work at the Institute of Aerophysics has come from the Defence Research Board, the United States Air Force, and A. V. Roe.

The research described covers a broad range. On the physical side, it embraces both fundamental and applied, and both theoretical and experimental investigations. These relate to the generation of sound by jets, wakes and boundary layers; to the suppression and reduction of such sound; and to its effects upon structures.

On the bio-acoustic side, investigations have been carried out into the effects of aircraft noise on voice communication and on hearing; into hearing conservation programmes; into noise protection criteria and ear defenders; and into the effects of hyperventilation on speech and hearing.

The paper is divided into two main parts, in which the physical and the bio-acoustic aspects are described separately.

PART A: PHYSICAL

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A.1. JET NOISE

Strength Distribution of Noise Sources along a Jet

Progress in the development of mufflers for jet noise has proceeded largely by empiricism (cf. Ref. A1) guided to a certain extent by Lighthill's basic theory (Refs. A2, A3). Curiously enough, it is only recently that the theory has been applied (in different ways, Refs. A4, A5; see also Ref. A6) to assess the distribution of noise-source strength along a jet; yet this information is basic to an understanding of jet-muffler action.

In the Canadian study (Ref. A5) Lighthill's theory is applied to the two regions of "similar" profiles in a jet. The analysis refers to the noise power emitted by a "slice" of jet (section between two adjacent planes
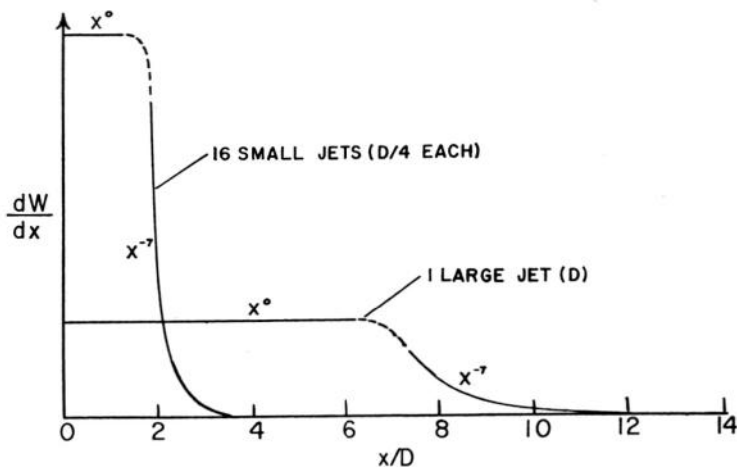

FIG. A1. Comparative noise power distribution of a single jet and a multiple-jet of the same total thrust.

normal to the axis) as a function of the distance x of the slice from the nozzle. It is found that this power is essentially constant with x in the initial mixing region (x^0 law), then farther downstream (about 8 or 10 diameters from the nozzle) falls off extremely fast (x^{-7} law of faster) in the fully developed jet (Fig. A1). Because of this striking attenuation of strength with distance, it is concluded that the mixing region produces the bulk of the noise and must dominate in muffler behaviour; conversely the "fat" part of the jet must contribute much less to the total noise power than is commonly supposed.

Powell's experiments (Ref. A7) on the effects of nozzle velocity profile on total noise power can thereby be interpreted qualitatively. The behaviour of multiple-nozzle or corrugated mufflers, both as to overall quieting and as to frequency-shifting, are also interpreted in the light of the results. Because the noise is concentrated near the nozzle (Fig. A1)
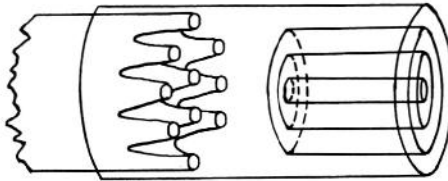

FIG. A2. Multiple-nozzle jet muffler plus sound-attenuating shroud.

the possibility emerges that such mufflers may be improved without serious thrust loss by the addition of a sound-attenuating shroud (Fig. A2).

Transmission of Sound to or from a Moving Medium

The details of the transmission of noise from a high speed jet to the surrounding quiescent air are not known. Lighthill (Refs. A2, A3) circumvents the details in terms of his Mach number factors for "self-propelled"
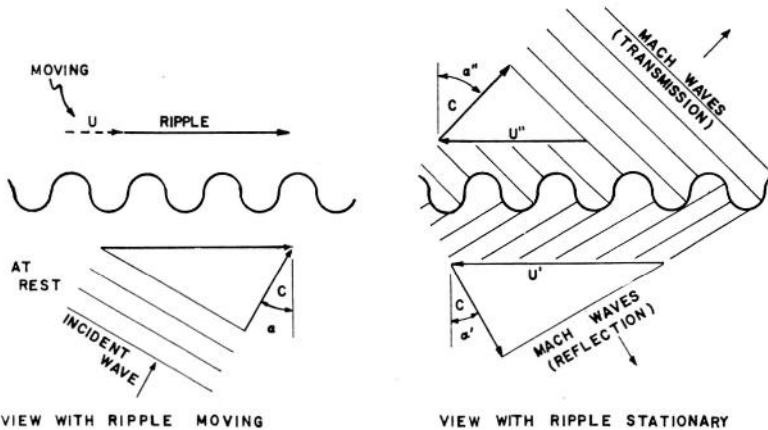

FIG. A3. Sound reflection and transmission by a moving medium in terms of Mach waves, generated by ripples running along the boundary.

noise sources (his analysis does not imply convection); however, the factors are open to suspicion in their prediction of infinite energy radiation at $M=1$. Thus some examination of the mechanism of the sound transmission is in order, starting with a much simpler case. The problem of the transmission of plane sound waves to or from a moving stream has been investigated in Ref. A8. The waves are specified as originating in air at rest and impinging obliquely on a plane interface with a moving stream. The analysis and the physical interpretation are both simplified by using axes moving with the ripple that must develop in the interface. The acoustic problem is thus changed into the aerodynamic problem of the flows above and below a wavy wall—the rippled interface (Fig. A3).

In this view the angles of incidence, reflection, and refraction are regarded as Mach angles in two supersonic streams. The velocity difference between these two streams is just the velocity of the original moving stream. The known angle of incidence thereby leads immediately to an equal angle of reflection and a simply-related angle of refraction (Fig. A4). The
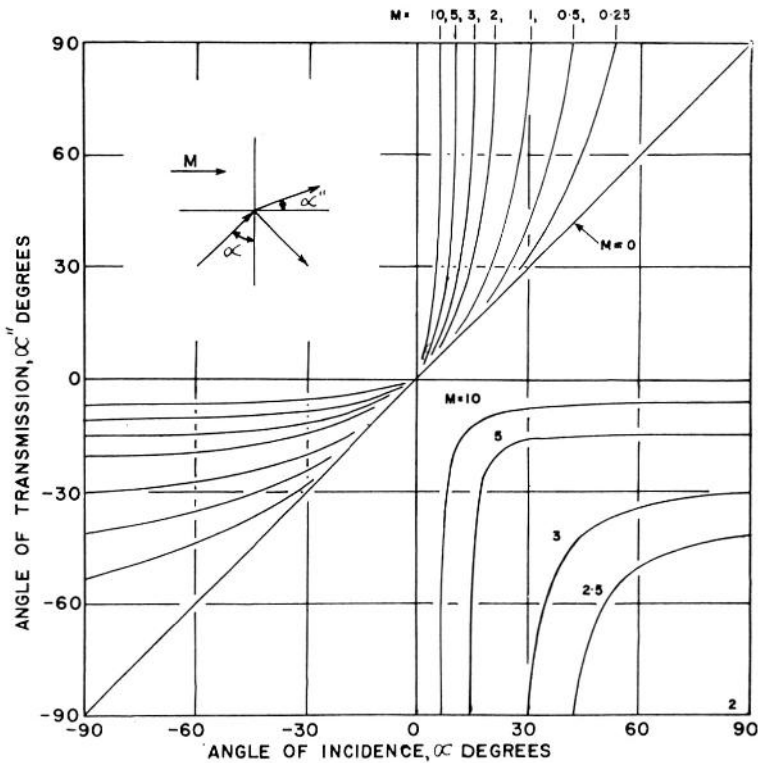

Fig. A4. Angle of refraction α'' vs. angle of incidence α for a series of Mach numbers of the moving medium.

angle of refraction is imaginary when the associated velocity, calculated by the velocity-difference rule, is subsonic. This is a condition of total reflection.

The amplitude relations (coefficients of reflection and transmission) are evaluated in closed form. In a graph three zones can be distinguished in the plane of angle of incidence vs. Mach number of the moving medium: ordinary reflection and transmission, total reflection, and amplified reflection and transmission (Fig. A5). Included are three loci of infinite reflection: i.e., self-excited waves. The energy balance is examined, and the source of amplification is concluded to be the energy of the moving stream.

Acoustic Energy Flow in a Moving Medium

It was remarked in the last section that Lighthill's Mach number factors for the moving sources in a jet lead to the unacceptable prediction of infinite energy radiation at a jet Mach number of unity. Thus the whole
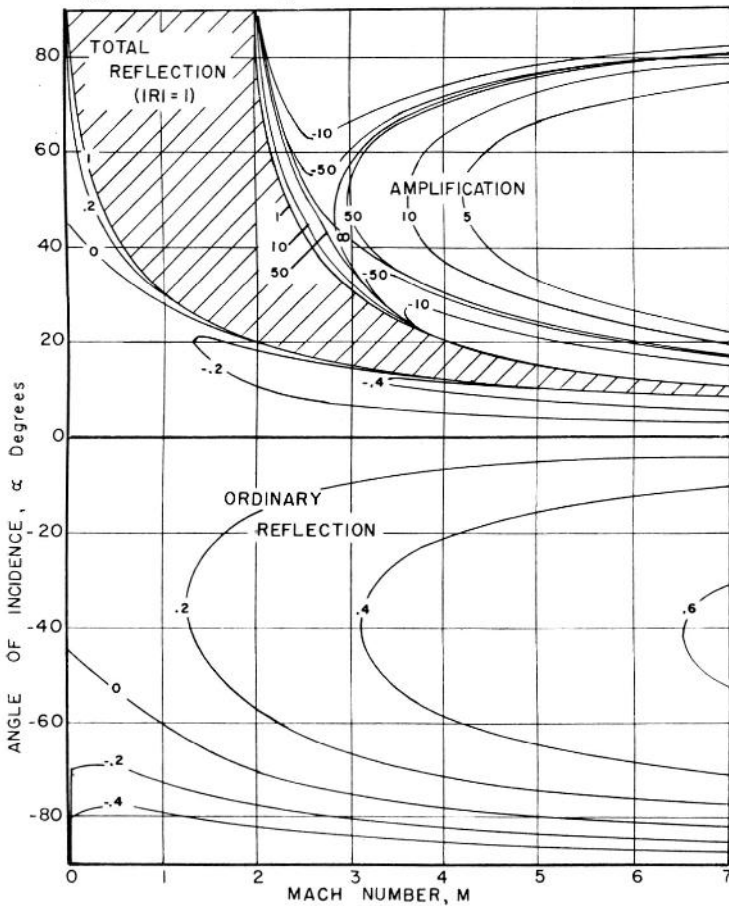

FIG. A5. Contours of constant reflection coefficient, R in a graph of angle of incidence vs. Mach number of the moving (second) medium.

question of acoustic energy flow in a moving stream must come under scrutiny.

It is known that both acoustic energy density and energy flow are modified by motion of the medium. The classical relation, acoustic energy flow equals pressure times velocity, applies only when the medium is at rest. The derivation of a corresponding relation for a moving medium offers some difficulty. Comparison has been made (Ref. A9) of similarities and discrepancies in the formulas of three investigators (Refs. A8, A10, A11) in order to infer a correct formulation.

A convenient form of such a formulation for plane sound waves is found to be:

$$\text{energy density, } \epsilon = \frac{\overline{p^2}V_f}{\rho c^3} \text{ (``linear theory'')}$$

$$\text{energy flow/unit area} = \epsilon \mathbf{V}_s \text{ (a vector)}$$

$$\text{(area taken } \perp \text{ energy flow)}.$$

This formalism is that of Ref. A10; that of Ref. A8 is compatible, and that of Ref. A11 errs only by a multiplicative constant.
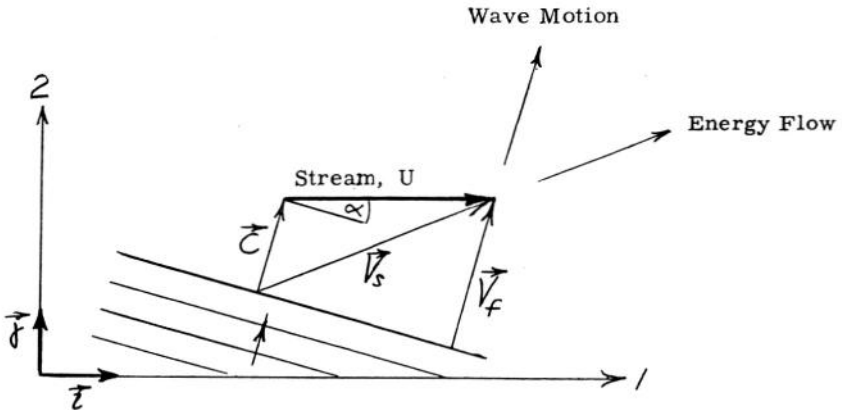

Fig. A6. Plane sound wave in a horizontal stream. The planes of constant phase move with the "phase velocity" $\mathbf{V}_f$ different from the ordinary speed of sound c. The acoustic energy flows with the "ray velocity" $\mathbf{V}_s$.

These formulas for a moving stream can be illustrated with the aid of Fig. A6. The planes of constant phase move with the "phase velocity" V_f different from the ordinary speed of sound c. The energy flows with the "ray velocity" $\mathbf{V}_s$. Figure A7 shows how, for a given wave pattern, progressive variation of the stream velocity can change the "linear theory" acoustic energy density—which is proportional to V_f—from positive through zero to negative, with corresponding changes in the energy flow. For the particular case of zero acoustic energy density and energy flow

the convection has cancelled out the propagation so that the sound waves are stationary: they are the familiar "Mach waves" of steady supersonic flow.
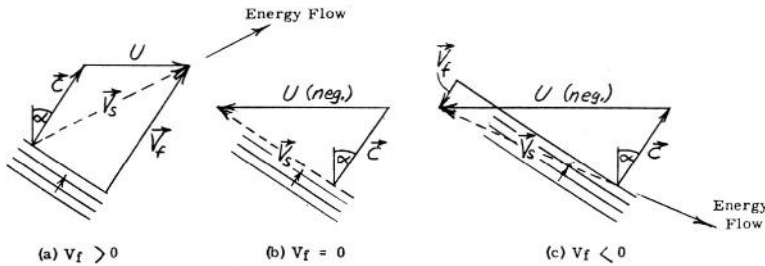

FIG. A7. Plane sound waves in a moving stream: effect of stream velocity U on phase velocity $\mathbf{V}_f$ and ray velocity $\mathbf{V}_s$. Acoustic energy density $\sim V_f$; acoustic energy flow V_f times $\mathbf{V}_s$.

Sound Generated by Interaction of a Single Vortex with a Shock Wave

It is well known that with the appearance of shock waves in a supersonic jet the noise emission is greatly increased, exceeding the U^8 law. (cf. Ref. A1). Theoretical studies have emphasized on the one hand a resonance effect (Ref. A12), and on the other hand the interaction of convected turbulence (created by the mixing) with the shock waves (Refs. A13, A14, A15).

The turbulence analyses do not provide a physical picture of what happens when a localized "eddy" passes through a shock wave. To simulate such a situation Hollingsworth and Richards made a Schlieren study of the passage of a single columnar vortex "broadside" through a shock wave (Ref. A16) and also presented an Heuristic theory (Ref. A17). The work to be discussed (Ref. A18) is an attempt at a quantitative theory of such an interaction.

The analysis exploits the concept that a vortex can be decomposed by Fourier methods into plane shear waves disposed radially like the spokes of a wheel (Fig. A8). Each of the shear waves interacts with the shock to produce a refracted shear wave and a plane sound wave according to previous work (Ref. A13) (Figs. A9, A10). The plane sound waves emanate, with varying angles, all along the shock front.

The plane waves possess an envelope that is essentially a growing cylindrical sound wave partly cut off by the shock (Fig. A10); that is, the pressure pattern peaks sharply at a cylindrical front (Fig. A11). The cylindrical wave is centered at the transmitted (and modified) vortex core and its peak attenuates inversely as the square root of the growing radius. The strength varies smoothly around the arc, from compression at one shock intersection to rarefaction at the other general shock intersection. These calculated characteristics appear to conform in a general way with a Schlieren photograph of the interaction process obtained in Ref. A16.
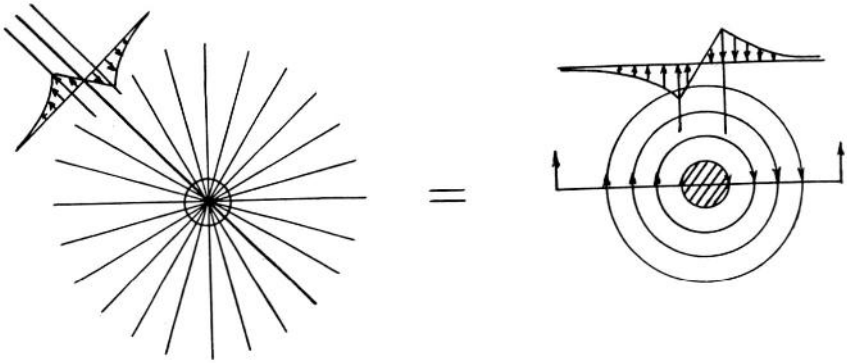
Fig. A8. Synthesis of vortex from radially disposed shear flows (physical interpretation of Fourier integral).
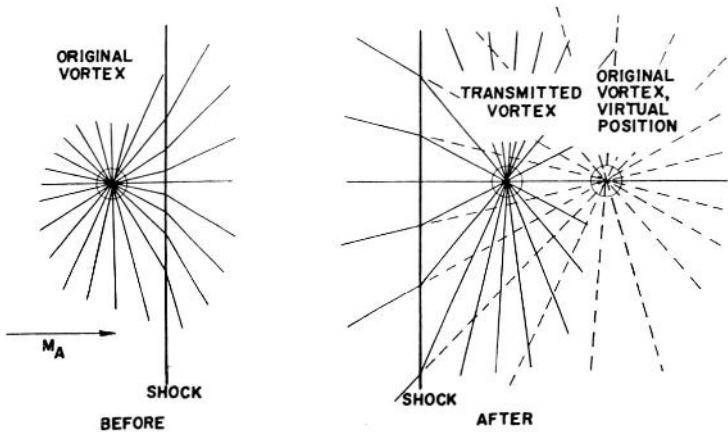

Fig. A9. Convection of vortex through shock wave, I: focusing of the refracted shear waves.
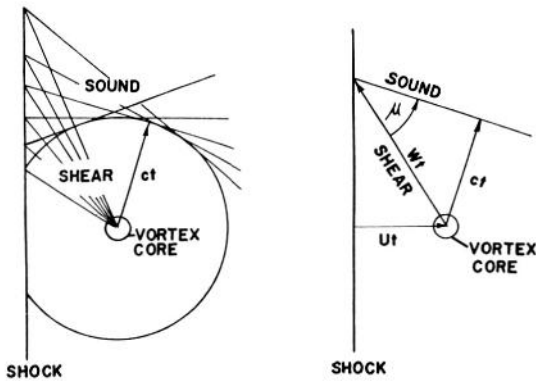

Fig. A10. Convection of vortex through shock wave, II: formation of envelope by plane sound waves generated at shock.

Ground Mufflers (UTIA Research)

One means of muffling a jet on the ground is to expand it in a diffuser. The small-diameter high-velocity jet is thereby converted into one having a large diameter and a low velocity. The eighth-power law indicates that the final jet will produce much less noise than the original one. Of course, the noise generated inside the diffuser may be very intense, and must be
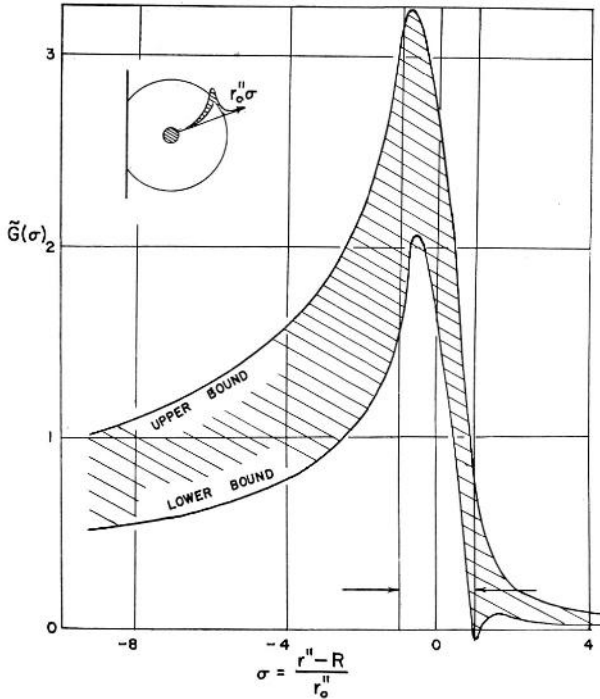
FIG. A11. Upper and lower bounds to radial pressure profile of cylindrical sound wave. (Shaded area for $\sigma > 1$ gives trend only, not bounds.)

absorbed by a suitable acoustic treatment. Since high pressure-recovery in the diffuser is not a factor, the application of short wide-angle diffusers appears attractive. One investigation along these lines was reported by Green and Lilley (Ref. A19) who found that the diffuser would run full if screens were used to provide enough internal resistance. The UTIA investigation was independently conceived, although information about the Green–Lilley work was received during the course of the research. The UTIA experiment (Ref. A20) differed in one significant respect from that carried out at Cranfield. This difference was the inclusion of air augmentation in the model configuration (Fig. A12). This feature might be necessary in a full-scale muffler for cooling purposes.

After a number of trials, satisfactory aerodynamic performance was achieved with two screens ($\Delta p/q = 3 \cdot 45$) as shown in Fig. A13. It can be

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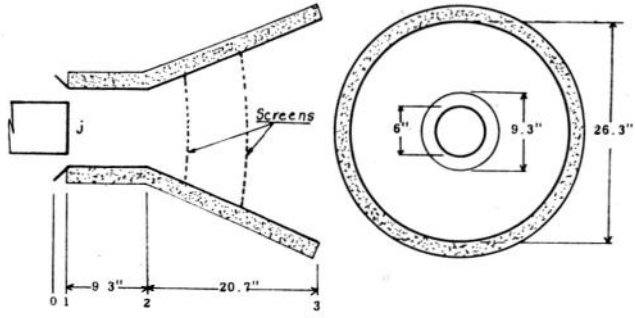
A_j ft.^{2}	$A_{1\text{-}2}/A_j$	A_3/A_2	$A_0/A_{1\text{-}2}$
0.79	2.40	8.0	2.25

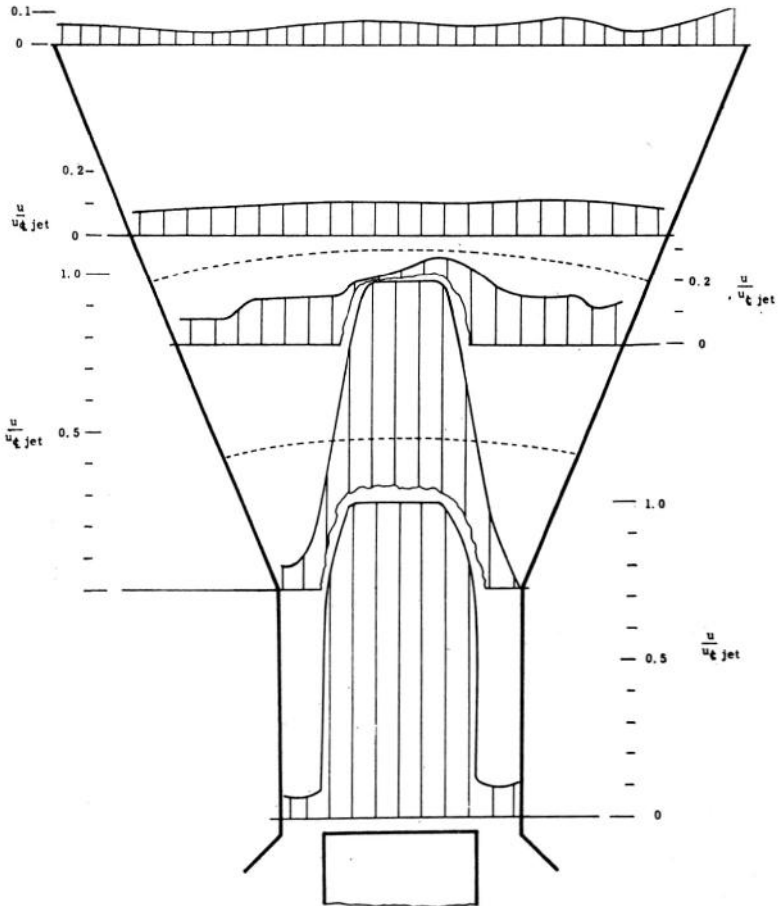Fig. A12. Axially symmetric muffler model.

Fig. A13. Velocity profiles.

seen that the diffuser did achieve the objective of producing a fairly uniform low-velocity exit jet. The induced flow achieved was 13·4% of the jet flow. A theoretical analysis given in Ref. A20 indicates that the velocity profile at the diffuser inlet is an important factor in determining the magnitude of the induced flow, and that a longer mixing length would increase it.

The acoustic performance of the model muffler tested was poor, in that more noise was generated with it than without it. This is attributed to inadequate acoustic design of the muffler walls. The Green–Lilley experiment was quite successful in this regard.

On the basis of the work cited, it would appear that wide angle diffusers could be developed into successful mufflers.

Ground Mufflers (Orenda Engines Research)

Orenda Engines Ltd. undertook the development of a light portable ground muffler which would be suitable for use with afterburning engines and which would provide a moderate attenuation. The program began with experiments on models, and progressed to full-scale testing of the configuration which evolved (Ref. A21). The muffler tested is shown schematically in Fig. A14. It consists essentially of a diffuser, which contains hollow baffles through which outside air is drawn into the flow. The resistance of the baffles is such that the flow remains attached to the walls. In this respect it is similar to the screened diffuser described above.
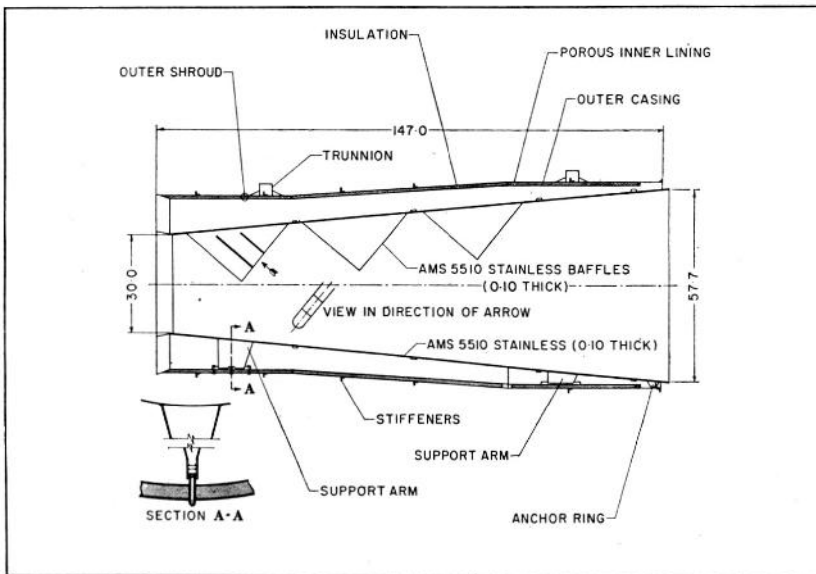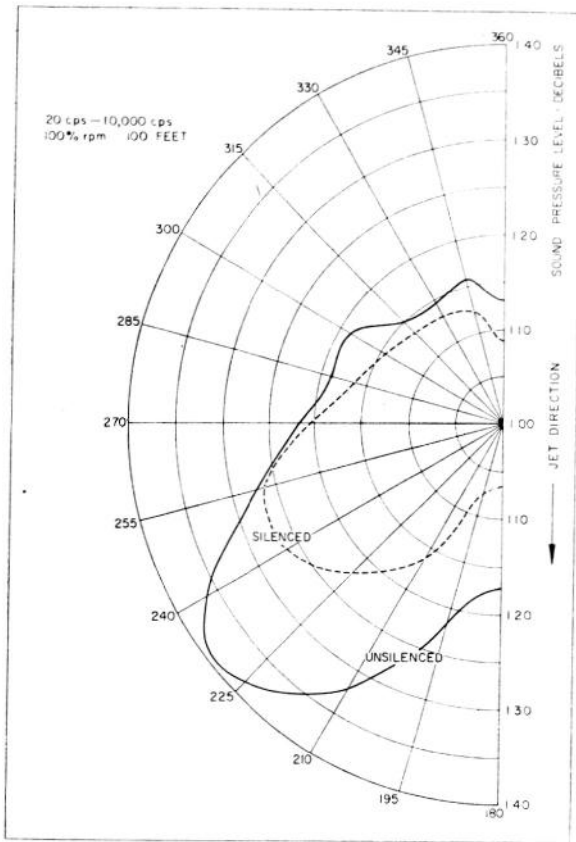

FIG. A14. Full-scale silencer.

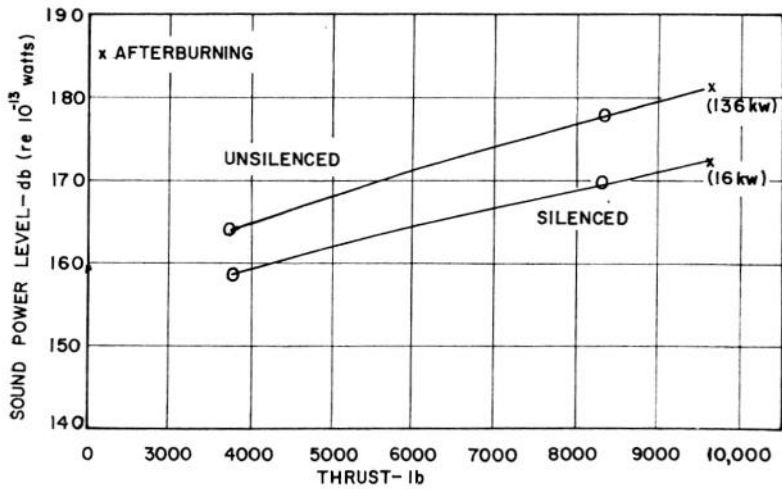Fig. A15. Polar diagram of CF 100/Orenda 11R noise field with and without silencer.

Fig. A16. Sound power level vs. Orenda 11R thrust with and without silencer.

Cooling is accomplished both by the air drawn through the baffles, and by the air aspirated through the inlet, which is about 60% greater in diameter than the jet exit. No deterioration of the muffler was observed after running with the afterburner lit.

The diffusion achieved is sufficient, on the basis of Lighthill's AV^8 law, to produce very large reductions (of the order of 30 dB) in the noise of the emergent jet. The actual reductions achieved are of the order of 15 dB at 100 ft radius, and 45° from the jet axis. A typical sound polar is shown in Fig. A15. It shows the characteristic field of the unmuffled jet engine and the reduction achieved by the muffler—the peak SPL is reduced from 139 dB to 127 dB. The effect of the muffler on total sound power is shown in Fig. A16—the power level is reduced by 9·3 dB in the afterburning condition. Additional development of the muffler is expected to produce further gains in performance.

A.2. BOUNDARY LAYER NOISE

Rigid Wall: Rotating Cylinder Investigation

The aerodynamic noise radiated by a turbulent boundary layer flowing over a rigid surface (one that cannot add to the sound by vibrating) is known to be relatively weak; thus it is easily masked by other noises, particularly in a wind-tunnel. An experimental arrangement that avoids
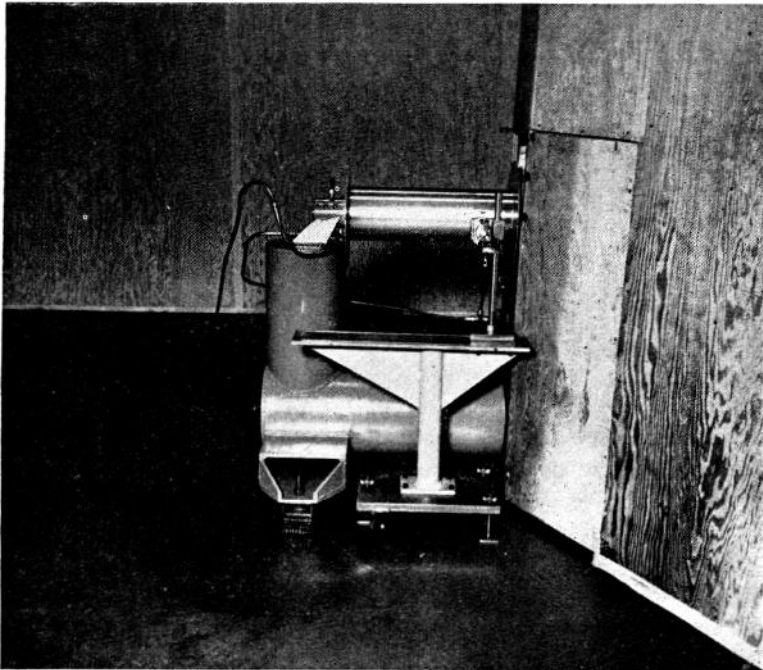

FIG. A17. Rotating cylinder and boundary layer traverse gear.

this masking by other flow-produced noises utilizes the turbulent boundary layer on a rotating cylinder. An investigation of the noise produced by such a boundary layer has been under way for some time at UTIA, conducted by L. N. Wilson.

The rotating-cylinder arrangement is shown in Fig. A17. The cylinder is a thick-walled tube of aluminium 6 in. in diameter and 18 in. long, mounted in journal bearings. It is belt driven and has been run at speeds up to 16,000 r.p.m. The heavy supporting structure (Fig. A17) was enclosed in a heavy plywood sound-isolating box filled with sand for the tests reported below. The cylinder assembly is installed in a reverberant chamber that can be calibrated for measurements of total sound power.
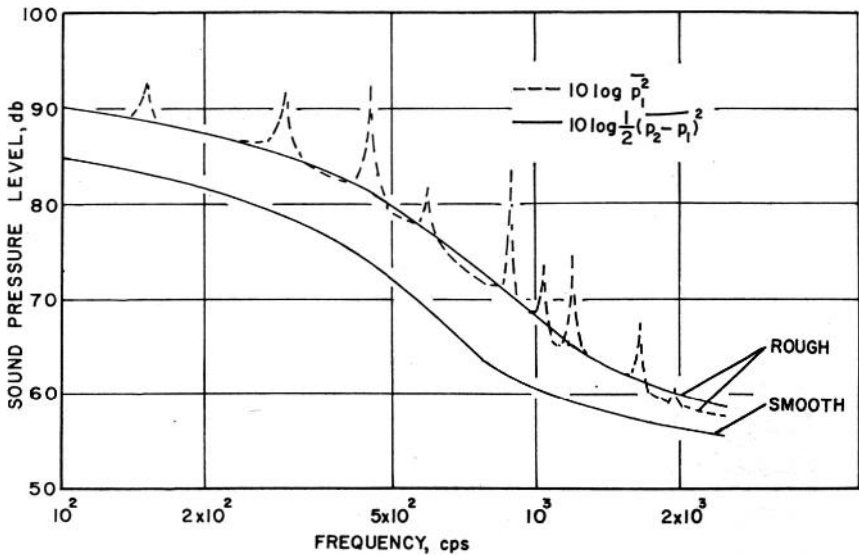
FIG. A18. Spectra of near field boundary layer noise pressures for smooth and rough 6 in. rotating cylinders, measured with a single microphone $(\bar{p}_1^2)$ and with anti-correlated microphones $\frac{1}{2}\overline{(p_2-p_1)}^2$ spaced $\frac{7}{8}$ in. apart. Distance from surface 2 in. 3% bandwidth analysis.

A typical near field spectrum with a single microphone (Fig. A18) exhibits a number of sharp peaks projecting above a broad-band continuous spectrum. These peaks occur at multiples of the rotation frequency. Cylinder unbalance and slight out-of-roundness would appear to account for such harmonic peaks. These effects and bearing imperfections can lead to rigid-body modes of motion of the cylinder.

The sound pressures associated with these modes ("bearing noise") would be expected to be correlated over large areas of the cylinder whereas that from boundary layer turbulence would be correlated over relatively small areas, the size of an "eddy". Therefore two microphones were placed close together near the cylinder surface and one-half the square of the *difference* between the signals was measured. The correlated "bearing

noise" should then cancel out, leaving only the uncorrelated noise, which is presumably the true boundary layer noise.

Such two-microphone (anti-correlation) near-field measurements are shown in Fig. A18 together with single microphone measurements. One curve refers to the cylinder in the smooth condition, using two micro-phones and the others to the cylinder roughened with aluminum oxide particles of about 0·007 in. to 0·009 in. height (No. 80 Alundum grains) using one and two microphones. The particles were sprayed on the surface in a shellac vehicle. It is clear that roughening raises the levels substantially, as might be expected. The wide-band noise between the harmonic peaks can be identified as true boundary layer noise because of the agreement there of the single and double-microphone curves. The peaks, which appear only on the single-microphone curve, are the extraneous "bearing noise".

The rough-wall curve of uncorrelated pressure (true boundary layer noise) Fig. A18, has been replotted in Fig. A19 on the basis of db/cycle vs. nondimensional frequency fD/U (Strouhal number). This and other curves obtained for speeds from 7000 to 13,000 r.p.m. have been adjusted to the same effective speed (10,000 r.p.m.) and superposed.
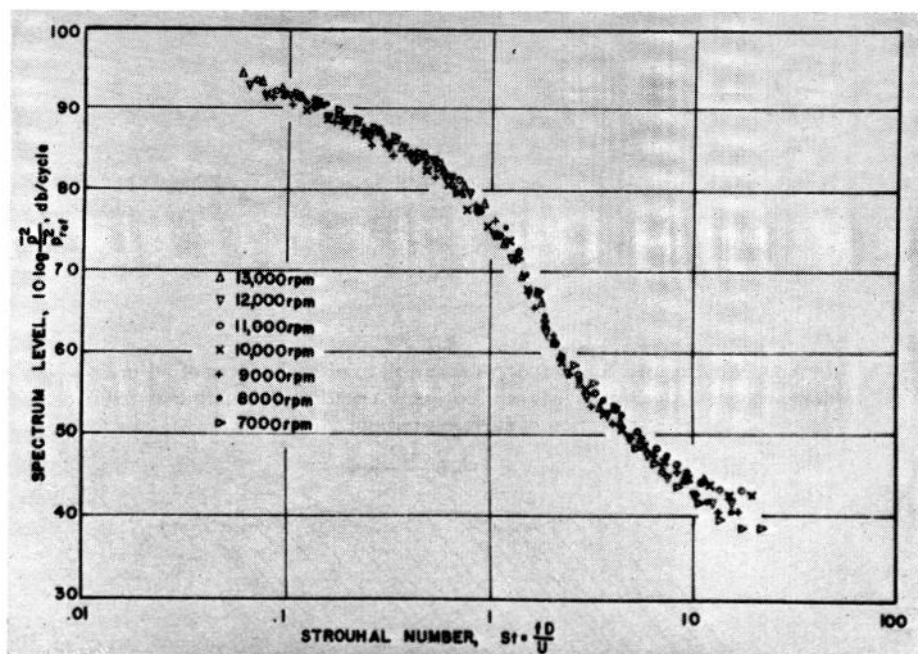

FIG. A19. Spectrum of near-field boundary layer noise for rough cylinder with anti-correlated microphones 2 in. from surface. Data for 7000 r.p.m. to 13,000 r.p.m. adjusted to 10,000 r.p.m. on basis $\bar{p}^2 \sim U^4$.

The relation $\overline{p^2} \sim U^4$ assumed in the adjustment is confirmed by the collapse of the points to a single curve in Fig. A19. Cross-plots of db/cycle vs. U for fixed fD/U further confirm a U^4 law. Apparently, then, the near-field boundary-layer noise is essentially the hydrodynamic (i.e. incompressible) pressure field associated locally with the eddying flow, for which $\overline{p^2} \sim \rho^2 U^4$. Blokhintsev, who has discussed such pressure fields, calls them "pseudo-sound" (Ref. A10) (see also Ref. A22).

Boundary Layer Noise Theory for Flexible Skin

The weak noise radiated by turbulent flow past a rigid wall—e.g. the rotating cylinder described above—is greatly augmented if the wall can vibrate, like the skin of an airplane. At high subsonic speeds such skin vibration is, in fact, reported to be the major source of noise within the aircraft (Ref. A23).

A theoretical study has been made (Ref. A24). The skin vibration is considered to be excited by the fluctuating hydrodynamic pressures in
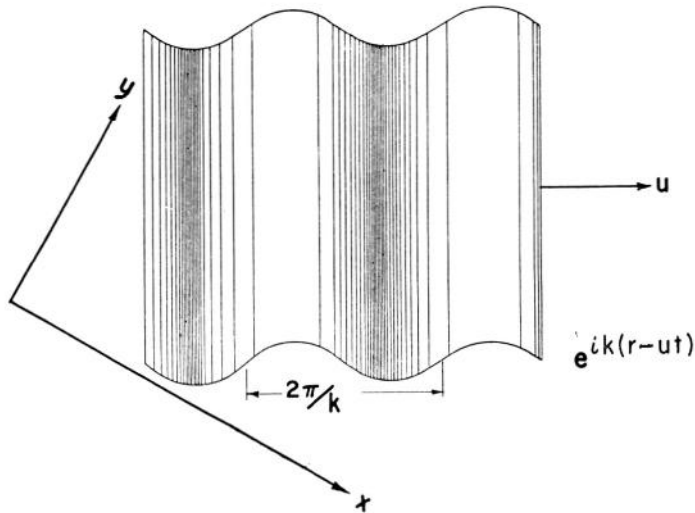

FIG. A20. Moving pressure wave. An assemblage of such waves of all orientations, wavelengths and speeds can represent a random fluctuating distribution of surface pressure.
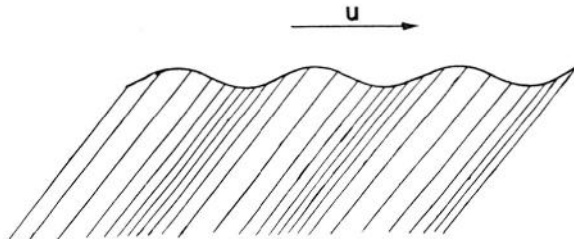

FIG. A21. Generation of Mach waves by flexural wave traveling with supersonic speed along plate. (Upper family omitted.)

the turbulent boundary layer. These "pseudo-sound" pressures greatly exceed the associated compressibly-generated pressures that are radiated as sound in the rigid-wall case; this accounts for the amplified radiation provided by the sounding-board effect of a flexible wall.

The fluctuating pseudo-sound pressure distribution can be decomposed by Fourier methods into a pattern of sinusoidal pressure waves with various angles of yaw (Fig. A20). The pattern is idealized as rigid and moving uniformly by convection (the pressure fluctuation at any point is thus caused by the motion). A running ripple in the skin follows underneath each wave, and the noise is ultimately due to these ripples. The acoustic effects of the running ripples have been determined for an *infinite* plane sheet. Supersonically moving ripples radiate strong sound in the form of Mach waves (Fig. A21); subsonically moving ripples generate no sound unless the sheet is finite (or the ripples unsteady).

FIG. A22. Boundary-layer-induced noise pressure levels calculated for example airplane along centerline of aft end of fuselage. Highly reverberant conditions, no insulation. Altitude 18,000 ft, fuselage pressurized to 8000 ft.
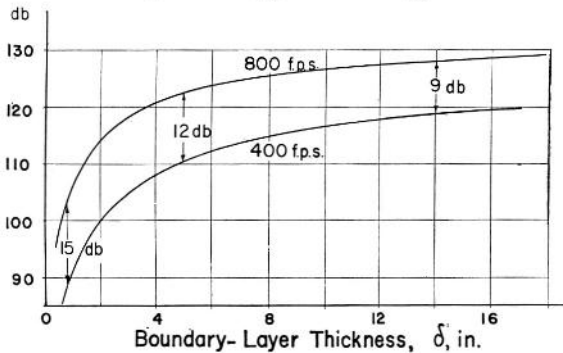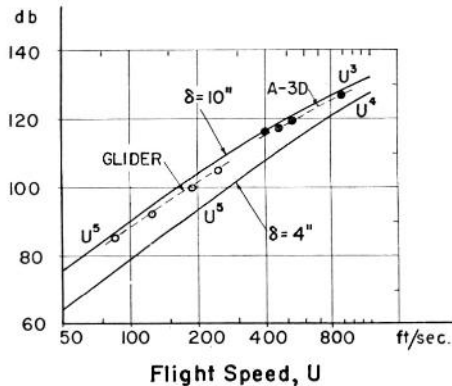

FIG. A23. Boundary-layer-induced noise pressure levels calculated for example airplane along centerline of aft end of fuselage. Highly reverberant conditions, no insulation. Altitude 18,000 ft, fuselage pressurized to 8000 ft. Experimental points are corrected for altitude.

For an airplane fuselage, however, the infinite plate is replaced by a succession of finite panels. Successive panels are considered to be statistically independent because the running waves are interrupted by the frames and stringers supporting the skin. Moreover, multiple reflections at the frames and stringers convert the running waves into standing waves. An assumption is used to link the two kinds of waves, and this leads to provisional estimations of noise levels within aircraft. On this basis the mean square noise pressure is predicted to vary as $U^5\delta^3/h^3\eta$ for thin boundary layers, changing progressively to $U^3\delta/h\eta$ for thick layers or high speeds (U=flight speed, δ=boundary layer thickness, h=panel thickness, η=panel damping coefficient). A common factor, $\rho^2\rho_e^2/\rho_p^2$ has been omitted for simplicity from both formulas where ρ=interior air density, ρ_e=exterior air density, ρ_p=panel density.

It is clear that increasing the panel damping η is a powerful means for reducing the noise. For the fixed value $\eta=0\cdot01$ the noise level formulas are illustrated in Figs. A22 and A23. Shown also on Fig. A23 are some experimental data for actual aircraft, adjusted to apply to the same pressure altitude. The close agreement with the $\delta=10$ in. curve is perhaps fortuitous in view of the uncertain correspondence of the parameters (e.g. η and δ) and the approximations in the theory.

Boundary Layer Noise Experiments with Flexible Skin

An acoustically-quieted air duct facility has been constructed at the Institute of Aerophysics, University of Toronto (UTIA) for the purpose of investigating noise generated by turbulent flow past a flexible panel; this is essentially the "boundary layer noise" the theory of which was discussed in the last section. In this duct the panel is to be fitted in a cut-out portion of one wall flush with the inner surface.

The facility is basically an open circuit acoustically lined wind tunnel with a 33 ft duct section (Figs. A23, A24). Any one of four interchangeable sections can be used, with respective inside cross-sections 12 in. wide and 8 in., 4 in., 2 in., or 1 in. deep to provide fully developed turbulent channel flow before reaching the test section. The test section passes through a reverberation chamber for measurement of noise power.

Maximum air speed with the 10 h.p. blower (4 in. duct) is 200 ft/sec. Details of the design and aerodynamic performance—e.g. velocity profiles and pressure gradients—are given in Ref. A24.

A set of exploratory noise measurements have been made with a steel panel 12 in. $\times$ 12 in. $\times$ 0·002 in. installed horizontally in the 8 in. duct. No great care was taken, and the thin panel as finally tested (crudely supported in a wooden frame) contained numerous irregularities or wrinkles in the surface. Sound pressure level readings were taken at heights $z=1\frac{1}{2}$ in., 6 in., 12 in., 30 in., 36 in. and 42 in. vertically above the centre of the panel. The readings in dB (re 0·0002 microbar) are plotted vs. air speed U at the duct inlet in Fig. A26. The curves seem
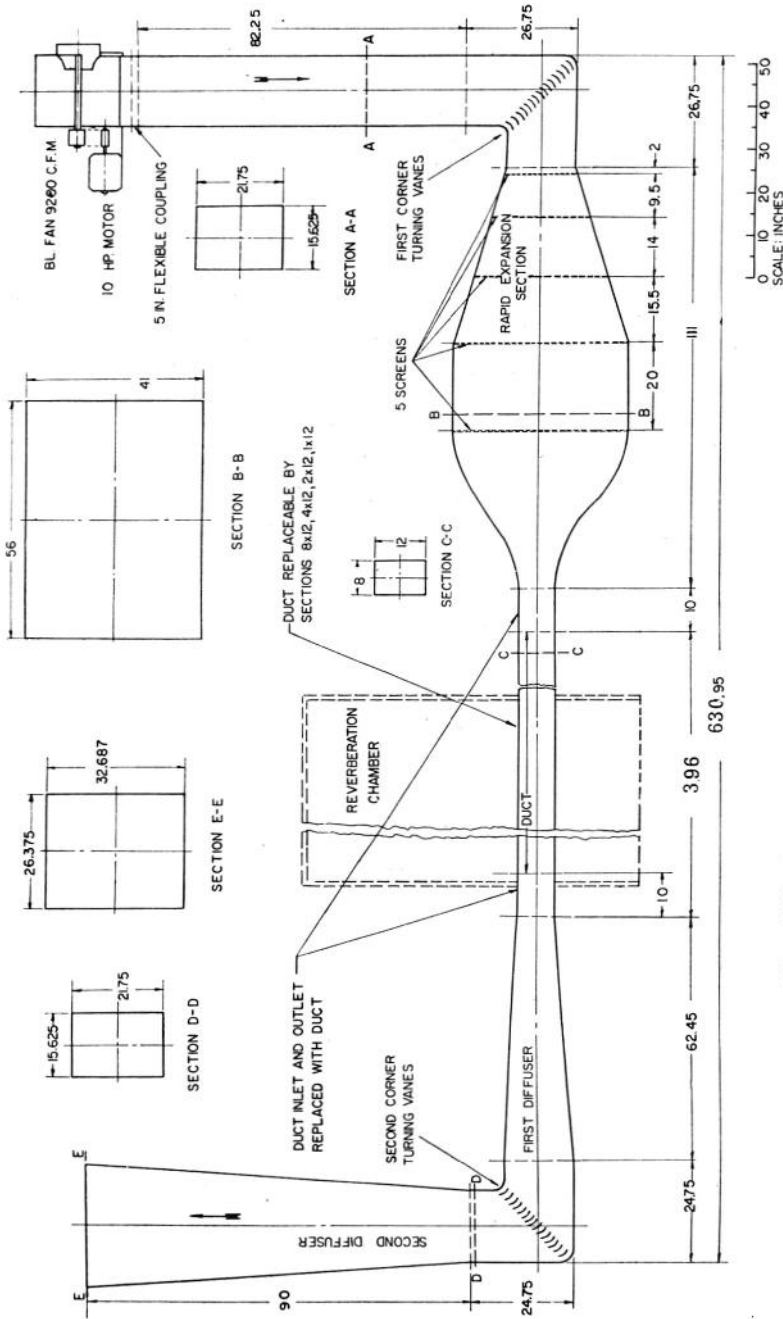
FIG. A24. General arrangement. Boundary-layer-noise duct.
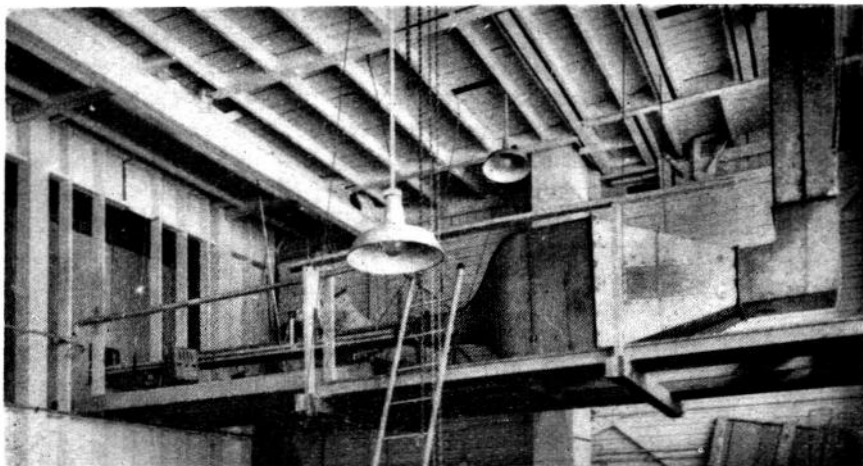
Fig. A25. General view of wind tunnel.

not to be inconsistent with the theory (Ref. A23) which predicts a U^5 law at low speeds with a transition to a U^3 law at high speeds. The theory is inadequate, however, in its present form, to predict quantitatively the position of the observed knee of the curve.

Tentative measurements have also been made on a second 0·002 in. steel panel carefully mounted under tension in a machined steel frame and free of wrinkles. Spectra and overall pressure levels for various air speeds are given in Fig. A27. The overall levels approximate a U^5 law. It is thought that the absence of a transition to a lower power may be due to the initial tension in the panel: the increased effective stiffness simulates the
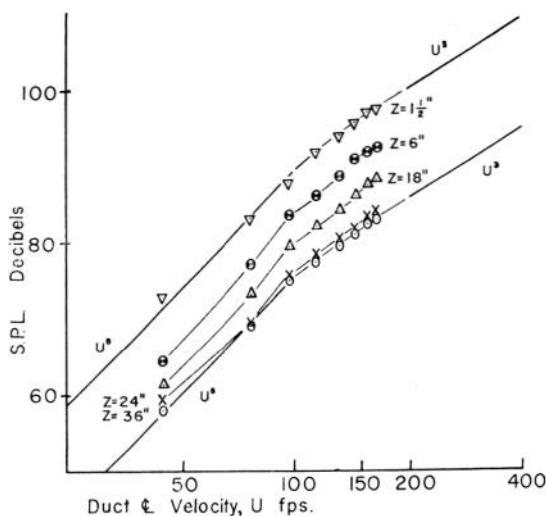
Fig. A26. Pressure level near panel.
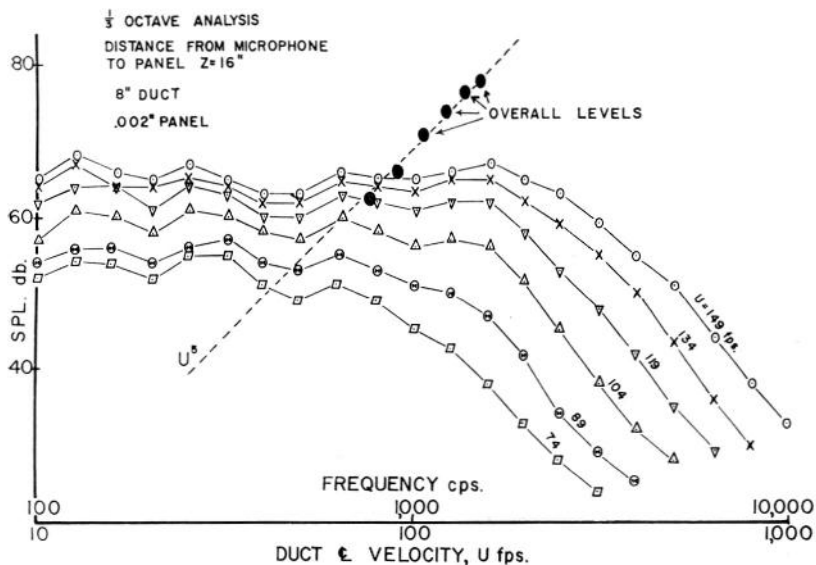
FIG. A27. Far field measurements of acoustic radiation from 0·002 in. steel panel.

properties of a thicker panel without tension, for which the transition point theoretically occurs at a higher air speed.

A.3. AEOLIAN TONES

One of the goals of research in flow noise has been the attainment of quantitative experimental verification of the theory. The classical phenomenon of aeolian tones, being relatively simple, offers an attractive possibility for such a verification, and therefore has received some attention both in Canada and the U.K.   Aeolian tones are the almost-pure notes emitted by a wire or circular cylinder placed in an airstream; they are closely associated with the periodic shedding of vortices into the wake.

A theoretical and experimental investigation was started at the UTIA in 1955 (Refs. A25, A26, A27, A28). Initially it comprised an adaptation of Lighthill's theory (Ref. A2) for application to the case in hand, and some measurements of the intensity and frequency of the radiated sound. It was soon found that there was insufficient information available on the unsteady pressures and forces acting on a cylinder to provide a good quantitative check on the theory. The program therefore continued with measurements of the pressures, the two-point correlations of the pressure, and the forces. Some details of the theoretical and experimental work follow.

Theory—Lighthill's equations (Ref. A2) could not be applied directly to the problem because of the presence of a solid boundary in the flow (the surface of the cylinder). The equations were adapted to apply to this

case by imagining that the solid cylinder is replaced by a column of fluid which is maintained at rest by a suitable distribution of body forces. The radiated sound field is then found to be that of a distribution of quadrupole sources associated with the turbulence in the wake, and of dipole sources associated with the body forces. The latter are uniquely determined by the surface pressures. This result is exactly the same as that obtained by application of Curle's theory (Ref. A29). It was assumed that in the experiments the quadrupole sound would be negligible compared to that from the dipoles at the cylinder surface. The theory then predicts that the principal radiation is a note at the fundamental frequency of the wake, radiating as a dipole with its axis cross-stream. This note is associated with the alternating lift force on the cylinder. A second note, at double the frequency, and associated with the drag fluctuations, radiates as a dipole with axis in the stream direction. The intensity of the sound in the far field varies approximately as the sixth power of the speed, and depends upon the magnitudes of the fluctuating forces and on their correlation along the length of the cylinder. No theory exists for predicting these forces and correlations.

Measurements of Intensity and Frequency

The experiments were carried out in the UTIA subsonic wind tunnel. A number of cylinders were used, varying from $\frac{1}{8}$ to $1\frac{3}{4}$ in. in diameter, and the speed range was from about 100 to 225 ft/sec. The results of the frequency measurements are shown in Fig. A28. They are in general agreement with results obtained by other investigators.
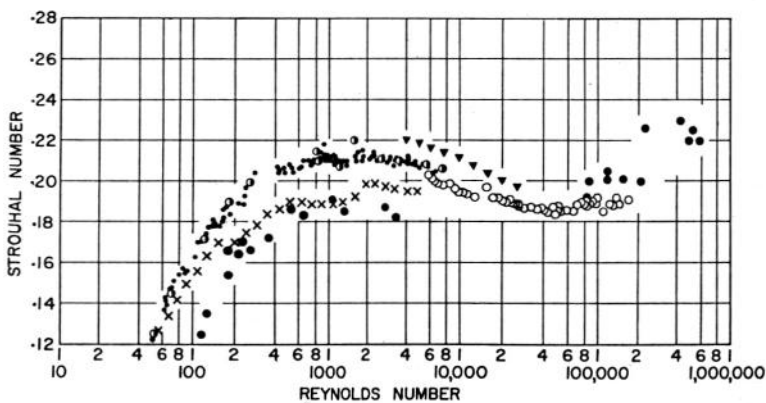
Fig. A28. Variation of fundamental Strouhal number with Reynolds number.

   ○ UTIA—1955
   ● Roshko—1953
   ◐ Kovasznay—1949 (after Roshko)
   ● Relf—1924
   ▼ DVL Hiebtone—1919 (after Lehnert)
   ✕ Strouhal—1878 (after Lehnert).
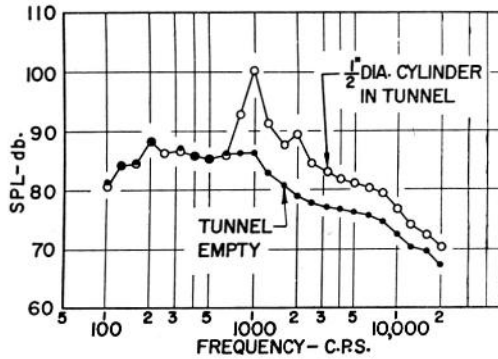
FIG. A29. Spectrum of cylinder noise. $\frac{1}{3}$ octave band analysis uncorrected for microphone response, $U = 225$ ft/sec, microphone in settling chamber.

Run No.	Description
○—100	cylinder in tunnel
●—101	tunnel empty.

Intensity measurements were made with the microphone both inside and outside the tunnel. A typical spectrum with the microphone upstream of the cylinder is shown in Fig. A29. The sound from the cylinder is seen to be significantly louder than the tunnel background and the peaks at the fundamental and second harmonic frequencies are clearly evident.
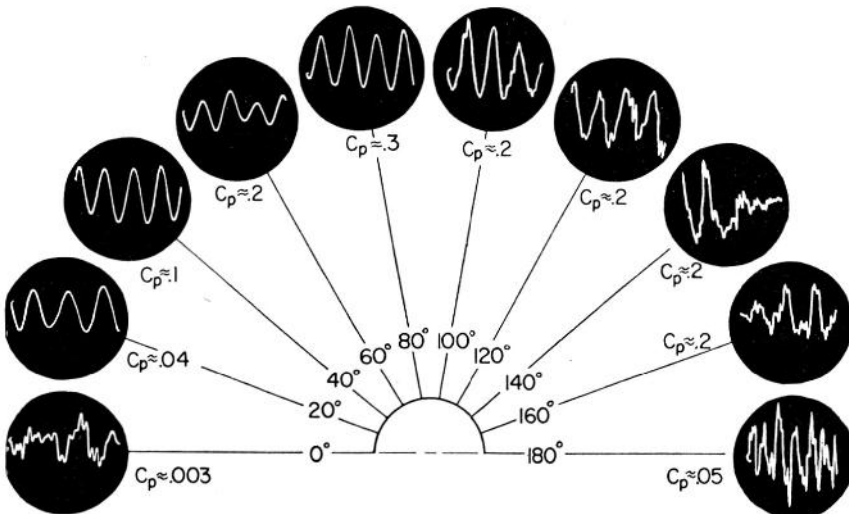
FIG. A30. Oscillograph pictures of overall pressure fluctuations at various locations around the cylinder. $U = 75$ ft/sec, bandwidth: zero selectivity.

Interpretation of these intensity measurements is somewhat difficult, because of an unknown reverberation effect. However, the order of magnitude is given by these measurements.

Measurements of the Pressure

The pressure fluctuations at the cylinder surface were measured by means of a condenser microphone installed internally. Typical results are shown in Figs. A30, A31, A32. These show the nature and magnitude
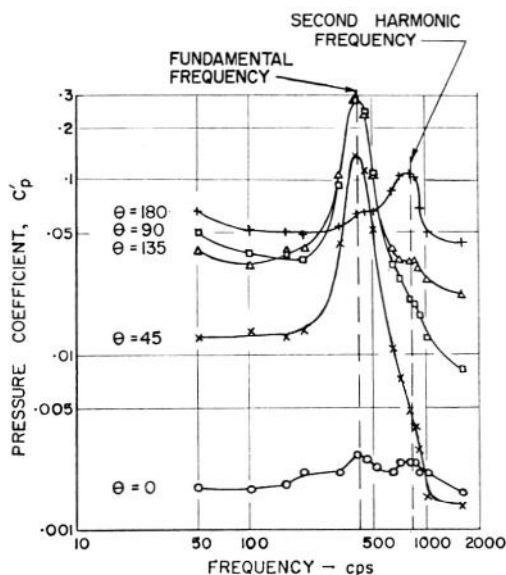
FIG. A31. Pressure spectra at various locations around the cylinder. $U = 211$ ft/sec, bandwidth: $\frac{1}{3}$ octave.

of the r.m.s. pressure, and how it varies around the circumference. The fundamental component dominates at the sides, and the second harmonic at the back. This is consistent with the presence of a lift at the fundamental frequency, and a drag at double that frequency. The curve labelled "theory" in Fig. A32 was obtained from a simple potential-theory model of the flow incorporating a periodic circulation (Ref. A26). It gives the shape of the pressure curves with rather surprising agreement.

Measurement of the Two-point Correlations

A series of measurements was made of the correlations of the pressure along the cylinder. Condenser microphones were used as pressure transducers, and the quarter-square method was used to obtain the correlation coefficients. A typical result, with the holes at 90° to the stream, is shown in Fig. A33. The correlation does not fall off to zero at large hole separations as was expected. Further experimentation is required to explain this result. Until such an explanation is forthcoming, it has been tentatively
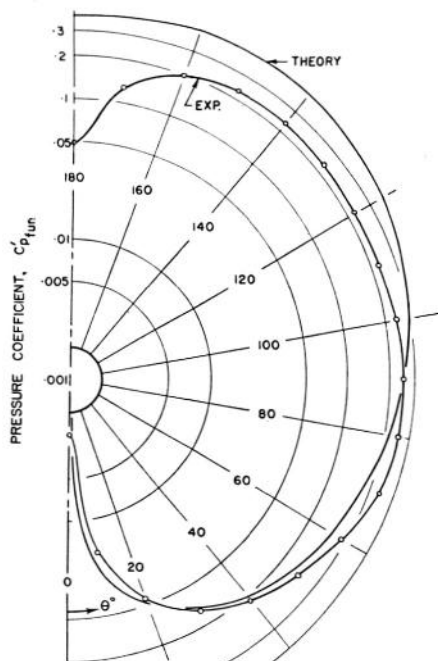
FIG. A32. Comparison of theoretical and experimental values of $C\acute{p}_{tun}$.
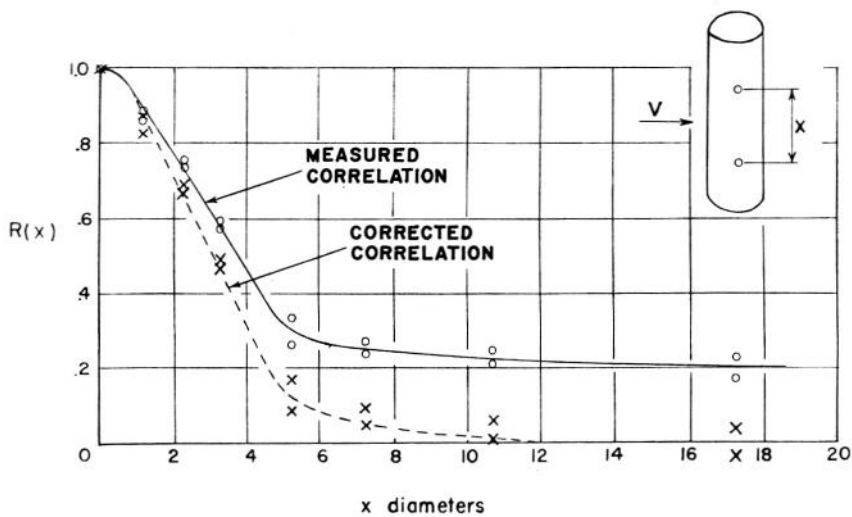
FIG. A33. Two-point pressure correlation on a 1 in. dia. circular cylinder. $U = 100$ ft/sec, $Re = 60,000$.
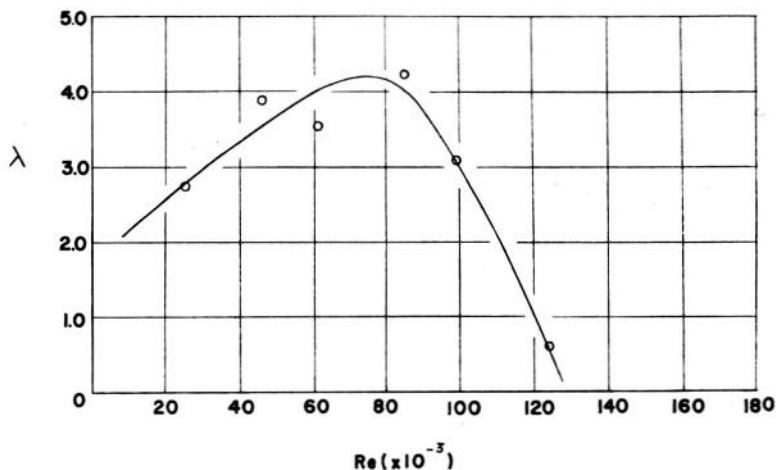
FIG. A34. Correlation length vs. Reynolds number for a 1 in. dia. circular cylinder.

assumed that the effect is caused by an unknown extraneous influence (possibly a tunnel wall effect). The correlation curve appropriate to free-field conditions has therefore been assumed to be given by the one shown broken in Fig. A33. The area under this curve defines the effective correlation length. Figure A34 shows how this correlation length varies with Reynolds number.

Measurement of the Forces

A strain gauge transducer has been designed and built for the measurement of the forces acting on a short section of the cylinder (one diameter in length). It is shown in Fig. A35. The transducer has been
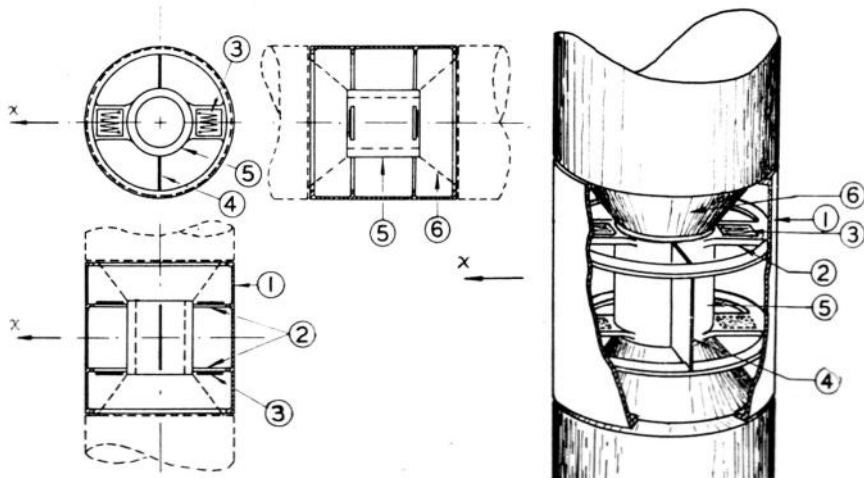
FIG. A35. Strain gauge balance for measuring unsteady components of lift and drag.

found to have satisfactory linearity, sensitivity, and repeatability. In order to calibrate it over the whole frequency range it has been necessary to use both mechanical and acoustical means to supply the calibrating forces. The acoustical loading required the development of a special calibration device.
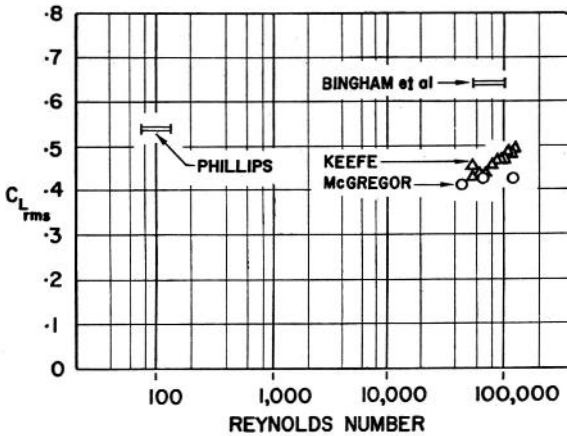
FIG. A36. R.M.S. lift coefficients.

Figure A36 shows the results obtained so far with this instrument (Keefe). It can be seen that they are in fair agreement with those estimated from the pressure distributions (McGregor), and with those of Phillips, obtained at a much lower Reynolds number. The results of Bingham *et al.* (Ref. A30) are in strong disagreement, however. Unpublished results obtained by Gerrard at Manchester are also in disagreement with those shown here. Gerrard's experiments were similar to McGregor's (Ref. A26), and this disagreement has not yet been explained.

Comparison of Theory and Experiment

The calculated values of the sound pressure in the far field are compared with measured values in Fig. A37. The data is presented in the form p^* as a function of Reynolds number. p^* is a non-dimensional sound pressure given by

$$p^* = 4\sqrt{2}\, p\, \frac{a_0}{\rho U^3}\, \frac{r}{\sqrt{ld}}$$

where p is the r.m.s. sound pressure, a_0 is the speed of sound in the undisturbed air, ρ is the density, U is the speed, r is the distance from the cylinder to the microphone, and l and d are cylinder length and diameter. The calculated value is given by

$$\sqrt{2\lambda}\, (C_L)_{\text{r.m.s.}}\, S_t$$

where λ is the effective correlation length in diametres, $(C_L)_{\text{r.m.s.}}$ is the r.m.s.
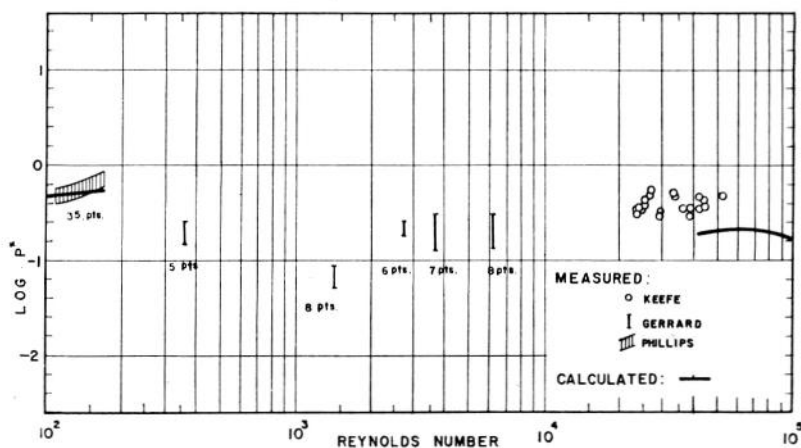
Fig. A37. Intensity of aeolian tones.

value of the lift coefficient, and S_t is the Strouhal number. The values of these quantities used for the calculated curve are those obtained in the UTIA measurements and those given by Phillips (Ref. A31). The intensity measurements shown are those of Keefe, Gerrard, and Phillips.

A.4. UNDERWATER NOISE

Studies of sound propagation in water have been carried out at the Pacific Naval Laboratory of the Defence Research Board. These have involved some investigations of flow noise, particularly in relation to the use of hydrophones being towed through the water. The noise associated with the wakes of connecting cables was found to be important. Studies have also been made of the noise produced by the flow over the hydrophone itself, and of the noise recorded by one hydrophone mounted in the wake of another.

A.5. NOISE INDUCED FATIGUE

Effect of Boundary-layer Noise

A previous section discussed how the turbulent boundary layer covering much of an airplane in flight can give rise to substantial noise in the interior by exciting vibration in the skin. The question has been raised whether the skin stresses associated with these vibrations are sufficient at the higher speeds to bring in the possibility of fatigue failure. A theoretical investigation of these skin stresses was therefore undertaken at UTIA under the sponsorship of Avro Aircraft, Canada, Ltd. (Ref. A32).

For all but very thick boundary layers the analysis was based on the idealized boundary-layer noise theory discussed earlier (Ref. A23). The procedures were modified and adapted to yield a tentative expression for
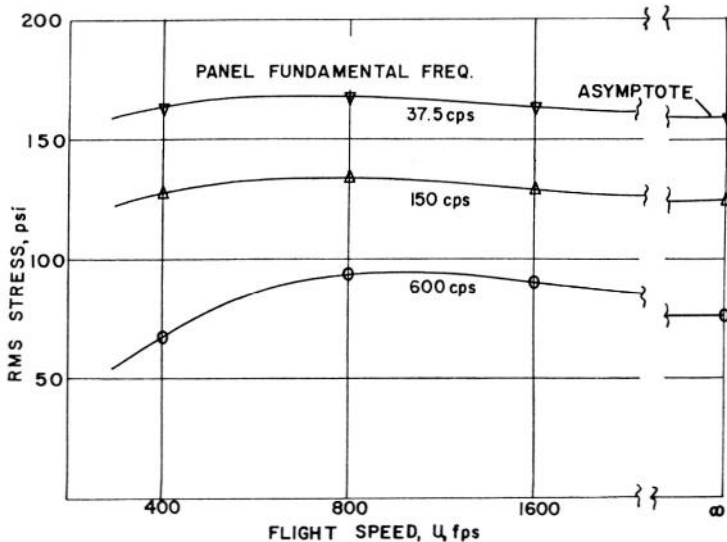
FIG. A38. Skin stress associated with boundary-layer noise according to example computations based on an idealized model. Dural skin 0·032 in. thick, boundary layer 4·27 in. thick, three sizes of panel (specified by resonant frequency).
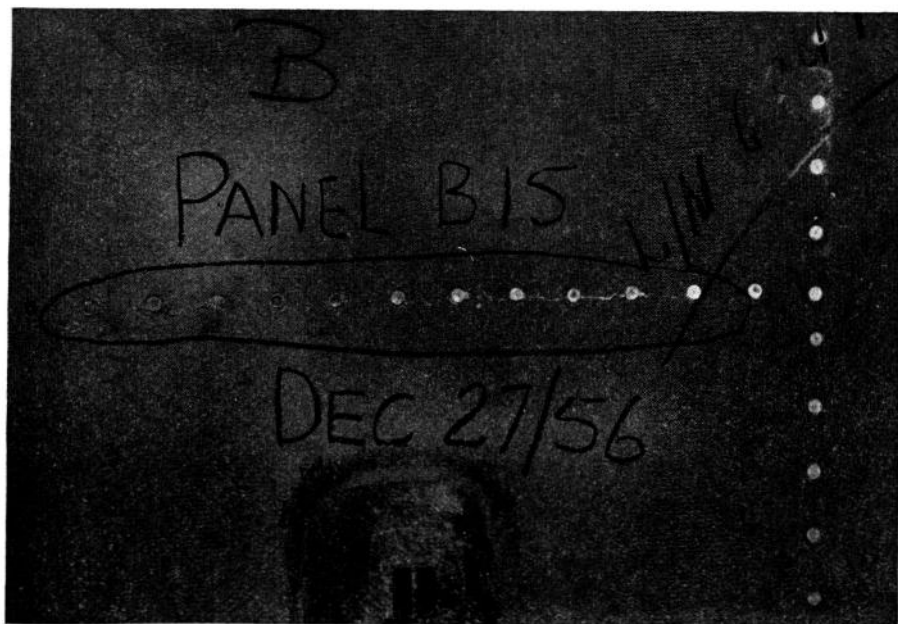
FIG. A39. Fatigue crack through rivet line (acoustic loading).

the mean square stress in the skin as a function of flight speed, boundary layer thickness, panel thickness, panel fundamental resonant frequency, damping coefficient, etc. A numerical example was worked out for 0·032 in. thick dural skin panels of three sizes (fundamental frequencies 37·5, 150, and 600 c/s, respectively), in which the flight speed was varied from 400 ft/sec to infinity with neglect of air damping and certain idealizations of the boundary layer. The boundary layer thickness was held constant at about 4 in.

The r.m.s. stress for these cases was found to be nearly constant over this entire speed range, showing a flat maximum in the range 700 to 1100 ft/sec (see Fig. A38). The maximum was far below typical "infinite life" endurance limits for dural type alloys (e.g. 10,000 lb/in² for an unfavourable static loading), never exceeding 170 lb/in². A supplementary study for extremely thick boundary layers (turbulence scale comparable with panel dimensions) was made by a one-dimensional approach developed from Miles' ideas (Ref. A33). Indications of r.m.s. stress exceeding 10,000 lb/in² were found for boundary layers several feet thick at supersonic speeds.
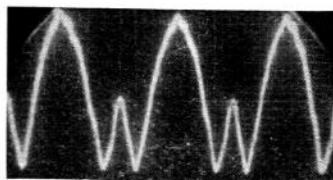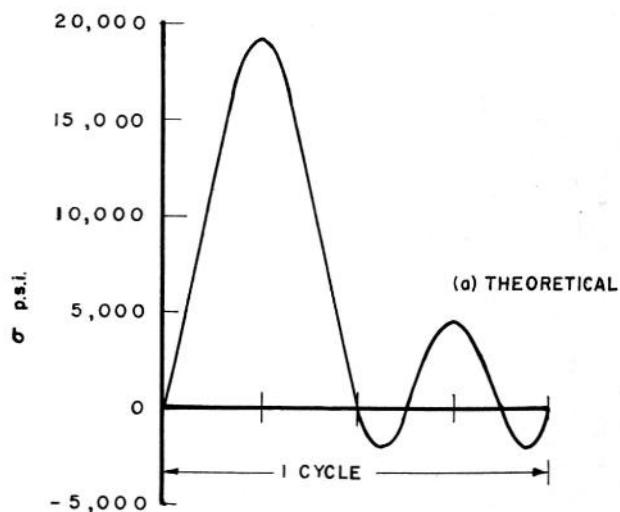
FIG. A40. Cyclic variation of fiber stress at center of panel with amplitude.

—— THEORETICAL STRESS FOR SAWTOOTH INPUT ($\mu = 0.31$)

---- ESTIMATED RANGE OF STRESS TO BE EXPECTED
FROM TEST DUE TO VARIATION IN TEST INCIDENT
WAVE FORM

O PANEL 8-CENTRE GAUGE
∇ PANEL 8-GAUGE AT x/D = .042
x PANEL 12-CENTRE GAUGE
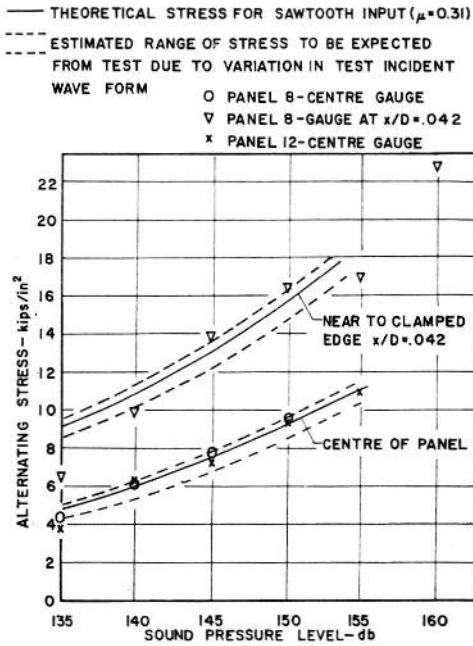
FIG. A41. Comparison of theory with test results.

—— THEORETICAL FREQUENCY FOR PURE
SAWTOOTH INPUT ($\mu = 0.31$)

△ PANEL 1
∇ PANEL 7   --- RANGE TO BE EXPECTED FROM TEST
O PANEL 8   DUE TO VARIATION IN TEST
X PANEL 12   INCIDENT WAVE FORM
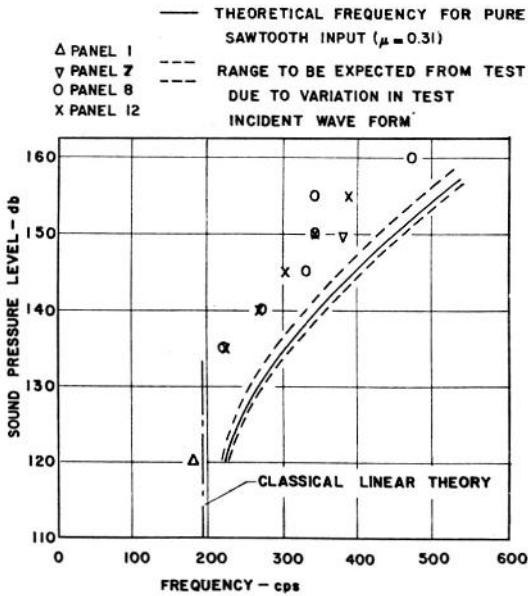
FIG. A42. Comparison of theory with test results—fundamental resonant
frequency vs. SPL.

Effect of Jet Noise

Experimental and theoretical investigations of noise-induced fatigue of built-up structures and simple flat panels have been undertaken at Avro Aircraft. The experimental work has been directed both at obtaining *ad hoc* fixes, and at verifying the theoretical calculations. The theoretical work has been directed at predicting the life of flat panels subjected to plane waves, normally incident.
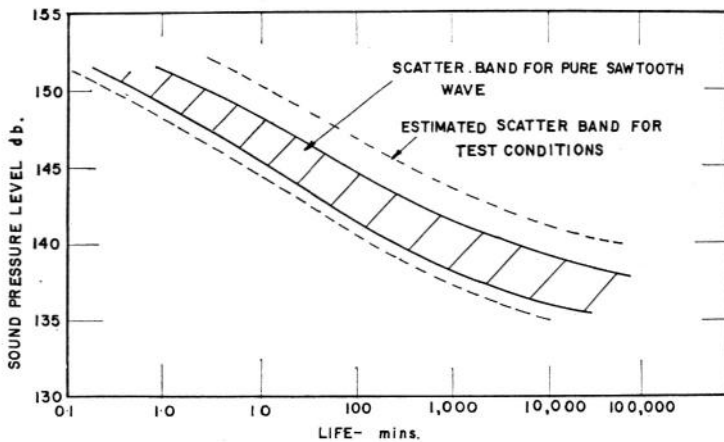
FIG. A43. Calculated test panel life vs. incident sound pressure level.

The testing has been carried out in a specially designed enclosure, using a siren to provide acoustic pressures of the order of 170 dB. The tests conducted on built-up structures indicated that the failures tended to occur in the supporting structure, at joints and in the skins through rivet lines (see Fig. A39). Generally, effective means of increasing the life were found to be: reduction of panel size, application of doublers (see Fig. A44) and introduction of additional damping.

The theoretical work (Ref. A34) has indicated that thin flat panels subjected to intense acoustic loading will achieve large enough amplitudes that both "plate-like" and "membrane-like" displacements and stresses coexist. The result is a stress-time curve such as that shown in Fig. A40(b). A non-linear theory has been developed to describe this phenomenon (Fig. A40a).
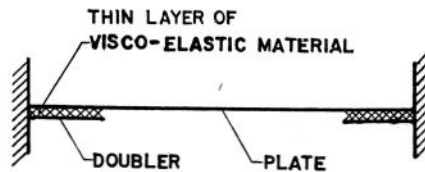
FIG. A44. Doubler-plus-tape damping scheme.

Comparison of Figs. A40(a) and (b) shows that the qualitative features of the panel behaviour are correctly predicted. A comparison has been made of the calculated peak-to-peak stress interval with measured values. The result is shown on Fig. A41, and the agreement is seen to be very good. The comparison of measured and predicted fundamental panel frequency is not so good however (Fig. A42).

The theory is applied to predict the fatigue life of flat panels subjected to periodic loading—an example is shown in Fig. A43. No experimental confirmation of these predictions is yet available. A result of some importance is the prediction that the use of a damping-tape plus edge doubler system (Fig. A44) can increase the sound pressure level for infinite life by 30 dB.

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Part B. Bio-Acoustic*

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INTRODUCTION

WITHIN the last decade bio-acoustic research into the effects on humans of exposure to noise has increased greatly in scope and importance. Bio-acoustics is defined for purposes of this paper, as that field of research concerned with the psychological and physiological problems of man and noise including the area of voice communications.

The overall levels of noise to which man is exposed has increased considerably over the past few years and has been accompanied by an increase in both the number of people exposed and the length of time of their exposures. Hazardous exposure to noise may result in temporary or permanent psychological or physiological damage to man. These effects may produce a reduction in the efficiency with which an individual can make calculations and decisions or operate various pieces of equipment, a reduction in efficiency which could result in the failure of a civilian or military operation.

Noise is defined as any unwanted sound. The magnitude of sound is measured in terms of sound pressure (dynes per square centimetre) or in sound energy (watts per square centimetre). The pressure level of sound, in decibels (dB) is 20 times the logarithim to the base 10, of the ratio of the pressure of the sound to the reference pressure. The sound pressure levels in dB, indicated in this paper, have a reference of 0.0002 dyn/cm² unless otherwise noted. Noise measurement data may be recorded and analysed in several ways (B19). One method often used as a basis for psychological or physiological research includes: (1) measuring the overall noise level and spectrum of the noise at the head level of the personnel occupying the area; (2) determining the source of the noise; (3) assessing the noise propagation patterns; (4) determining the distortion in the noise field due to the presence of the operators or other reflecting or absorbing structures; and (5) ascertaining the overall noise level variations as a function of time.

Canadian work in bio-acoustics includes (1) surveys of noise levels and spectra generated inside airborne aircraft and outside aircraft on the ground; (2) noise surveys of air bases; (3) studies of the effects of noise on hearing; (4) development of hearing conservation programmes; (5) assessment and development of methods and equipment for minimizing hazardous exposure to noise; (6) determination of the effect of noise and other masking stimuli on voice communications; (7) development of adequate procedures and phraseologies for domestic and international radiotelephony; and (8) assessment of the effects of hyperventilation on speech and hearing. Much of the research work is carried out by Government Organizations such as the Defence Research Board and the National Research Council with University and Industrial organizations also making a contribution.

AIRCRAFT NOISE

Recent noise surveys have indicated that inside various types of aircraft during flight under cruise conditions, overall noise levels are generated which range from 97 to 125 dB in propeller type aircraft, from 98 to 106 in Table B1 the overall noise levels are higher in the forward sections of jet aircraft (B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B21). As shown in Table B1 the overall noise levels are higher in the forward sections of propeller type aircraft, especially in the "plane of the propeller", than in the rear sections. The noise level distribution inside the turbo-propeller aircraft is similar. In jet aircraft, however, the area of highest overall noise levels is in the rear sections of the aircraft.

The spectra of the noise at various crew and passenger positions in propeller aircraft are more or less alike with most of the significant sound energy concentrated below 300 cycles per sec (c/s). The spectra of the noise measured in various types of aircraft at the pilots' position and at a position 6 in. from window 1 in the passenger compartment, are shown in Figs. B1 and B2. Inside jet aircraft during flight, the noise has its sound energy spread over a larger range of frequencies as is shown by the spectra of the noise of the COMET III and CF100 MK. III aircraft.

Outside propeller aircraft, the maximum noise levels, when measured under static conditions, are to be found in or near the "plane of the propellers". However, jet aircraft on the ground, under static conditions, generate maximum levels of noise at an angle of 120–150° (with zero designating the nose of the aircraft). The overall level of the noise, when measured on the ground varies considerably with the angle at which the noise measurements are made (see Table B2). For example, at a distance of 100 ft the overall noise levels generated by the CF-100 MK. IV vary from 115 dB at 0° to 137 dB at an angle of 135°. Similarly with the VISCOUNT aircraft the overall noise level varies from 112 dB at the front of the aircraft to 90 dB toward the rear. The distribution of sound energy
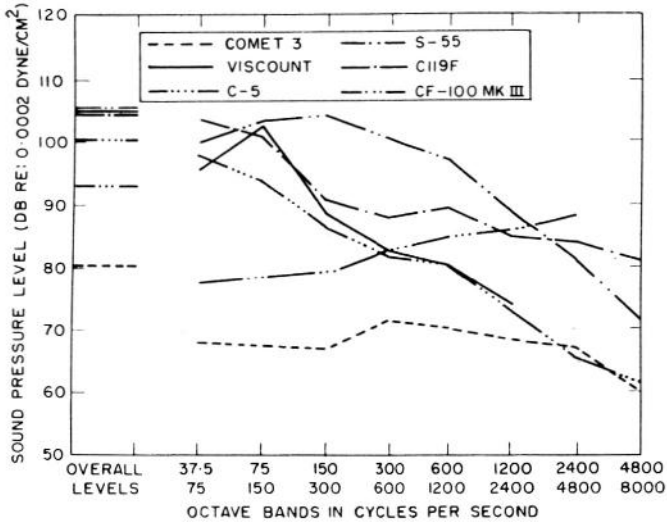
FIG. B1. Noise spectra, pilots' position, various aircraft, cruise conditions.
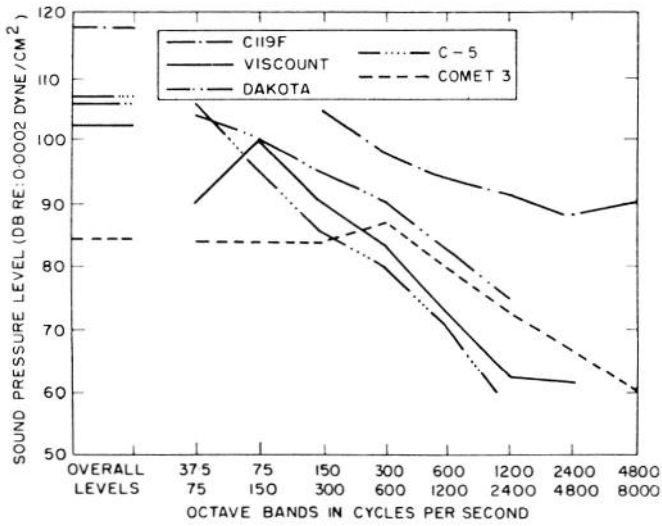
FIG. B2. Noise spectra, 6 in. from window 1, passenger compartment, cruise conditions.

TABLE B1

Overall noise levels, crew positions, various aircraft, cruise condition

Aircraft	Type	Position in aircraft							
		Pilot	Navigator	Radio operator	Nose gunner	6 in. from window 1	6 in. from window 3	6 in. from window 7
NORTH STAR (Standard)	4 Engines, Propeller	104	106	105		119	117	117
NORTH STAR (Acoustically Insulated)	4 Engines, Propeller	105	108	109		117	118	120
NORTH STAR (Acoustically Insulated with MacLeod Exhausts)	4 Engines, Propeller	103	107	104		107	103	114
C-119F	2 Engines, Propeller	107	108	109		118	115	114
CS2F	2 Engines, Propeller	94	103					
NEPTUNE	2 Engines, Propeller	103	103	98	98	99	96	96
C-5	4 Engines, Propeller	97	102	98		117	107	102

TABLE B1 (continued)

Overall noise levels, crew positions, various aircraft, cruise condition

Aircraft	Type	Position in aircraft						
		Pilot	Navigator	Radio operator	Nose gunner	6 in. from window 1	6 in. from window 3	6 in. from window 7
CANSO	2 Engines, Propeller	119	115	113				
DAKOTA	2 Engines, Propeller	107	110	109		107	104	
EXPEDITER	2 Engines, Propeller	115				113	111	
LANCASTER	4 Engines, Propeller	114	113	113	112			
MITCHELL	2 Engines, Propeller	119			110			
NORSEMAN	1 Engine, Propeller	116				115		
VENTURA	2 Engines, Propeller	121	119	119				
HARVARD MK. IV	1 Engine, Propeller	112	116					

TABLE B1 *(continued)*

Overall noise levels, crew positions, various aircraft, cruise condition

Aircraft	Type	Position in aircraft						
		Pilot	Navigator	Radio operator	Nose gunner	6 in. from window 1	6 in. from window 3	6 in. from window 7
VISCOUNT	4 Engines, Turbo-Propeller	106				102	98	99
COMET 1A	4 Engines, Jet	80	83	80		88	90	90
COMET 3	4 Engines, Jet	80	81	83		83	91	95
T-33	1 Engine, Jet	98	99					
CF-100 MK. III	2 Engines, Jet		94					
S-55 (Helicopter)	1 Engine, Propeller	108				105		
B-47 (Helicopter)	1 Engine, Propeller	108						
Airship "L" Type	1 Engine, Propeller	101						

in the noise measured outside aircraft also varies greatly with the position of measurement. With propeller or turbo-prop aircraft the sound energy measured at the front of the aircraft is distributed over higher frequencies than it is at the rear of the aircraft. Similarly, the distribution of sound energy generated by jet aircraft, varies with the angle of measurement. Under idling conditions, the sound energy measured at the front of a jet aircraft, is concentrated in higher frequencies than it is in the noise measured at the rear of the aircraft. Similarly as the thrust of an engine is increased the sound energy becomes more and more concentrated in the lower frequency bands.

TABLE B2

Overall noise levels, various aircraft, static conditions measured at 100 ft.

Aircraft	Measurement angle			
	0°	45°	90°	135°
CF-100 MK. IV (Jet)	115	155	120	137
T-33 (Jet)	100	107		117
F-86E (Jet)		106		118
F2H3 (Jet)	107	109	114	128
COMET (Jet)	124	128	112	128
NEPTUNE (Propeller)	110	109	102	106
VISCOUNT (Turbo-propeller)	112	101	95	90

Aircraft with much higher powered jet engines than those mentioned in the previous paragraph will come into service in the near future and will generate overall noise levels much in excess of those indicated above. For example, even at the present time, it is not uncommon for maintenance personnel to be exposed to overall noise levels exceeding 140 dB.

NOISE PROBLEMS OF AIR BASES

Noise, one of the problems now associated with the operation of air bases, will become even more acute in the future as more and more jet aircraft, both civil and military, come into operation (B22). The use of vertical take-off aircraft may reduce the levels of noise to which neighbouring communities are exposed but the use of rocket-powered aircraft will result in an increase which will require a radical change not only in the layout of air bases but also in air traffic control procedures.

Large jet aircraft produce greater levels of noise than those now being generated by large propeller aircraft and since jet aircraft flight patterns often differ from those of propeller aircraft, larger areas around air bases will be exposed to high-intensity noise for longer durations. In addition, as the volume of aircraft traffic increases the frequency of exposures will increase, which in turn, will result in an increase in the number and acuteness of the noise problems associated with air bases and surrounding communities.

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Preliminary procedures for airport noise surveys have been developed and the results of these surveys indicate that air bases can and should be so laid out that the administration offices, passenger reception and departure areas are isolated from the engine-test areas, runways and first-line maintenance areas (B2, B22). This will aid in minimizing the disruption of voice communication and interference with the "comfort" of air base residents, working personnel and airline passengers. Control towers should be located remote from sources of high-intensity noise such as maintenance, taxi-strips and take-off areas (B20). The proper use of adequate acoustical procedures and materials in the control towers will also aid in providing an adequate acoustical environment for voice communication and a more comfortable work environment.

Many other procedures can be used to minimize the noise problems arising from the operation of aircraft. Long-range planning will help to insure sufficient land being available for the isolation of air bases from residential areas. The use of longer runways will result in aircraft having a greater period of time to become airborne which could result in a reduction in noise, since the aircraft can take off at a reduced power. The proper zoning of land adjacent to air bases will also aid in minimizing the problems. For example the factories, especially aircraft factories built around air bases, will aid in providing a "buffer zone" between the noise source and the surrounding communities. Encouraging air base personnel to reside in residential areas near the air bases could provide such communities with residents less likely to be annoyed or irritated by noise. At least they would be less likely to complain.

Another method of minimizing the problem is to reduce the level of noise at its source. Ground noise-silencer installations, mobile and static, will afford a measure of noise attenuation with reductions of 30–50 dB being achieved. The reduction of the noise, at the source, in airborne aircraft has to date been relatively unsuccessful, with maximum reductions of 8 to 12 dB being achieved without a significant loss in thrust.

The problems associated with noise can be further minimized by reducing the number of ground "run-ups" and by scheduling them to take into account the sleeping and social habits of the residents in the nearby communities. The times that noise is generated by aircraft on the ground at air bases could also be reduced if the aircraft were towed from the landing strips to and from the passenger reception and departure areas or maintenance areas.

Another problem that may assume more importance in the future is that of damage to buildings from blast waves generated by aircraft flying at supersonic speeds at low altitudes. There is evidence that such blast waves will not only cause antagonistic responses from individuals who are exposed but may also cause damage to buildings if the aircraft is flying below 5000 ft. To aid in overcoming this danger, administration, passenger reception and departure, maintenance, etc., buildings could be located

underground. This underground placement of air base buildings will also be appropriate for the operation of rocket-engine aircraft.

One of the most important measures that can be taken to minimize antagonistic community responses to air base noise is the initiation, development and carrying through of an efficient information program. Keeping the public informed of the importance of aviation and particularly of the measures being taken by the air base management, airline and Air Force operators to reduce the levels of noise and thus minimize the hazards and irritation occasioned by the aircraft noise is of the utmost importance.

EFFECTS OF NOISE ON HEARING

Hearing is a very important sense. Without it, one's ability to communicate with other individuals and to maintain adequate contact with one's environment may be seriously impaired. While hearing acuity may be decreased by other influences such as ageing, disease or injury, noise is now recognized as being one of the main causes of hearing impairment. It is most difficult, however, to distinguish hearing losses due to non-noise factors from those occasioned by exposure to noise.

There are a number of data, both clinical and experimental, which indicate that lifetime exposure to jet or piston-engine noise whose overall level exceeds 85 dB may cause permanent hearing loss. The threshold of pain which occurs at approximately 130 dB for most individuals, has often been used, as an index of whether a noise was harmful or not. However, this threshold is approximately 40–45 dB higher than the threshold for damage to the hearing mechanism produced by lifetime exposure to noise. The amount of damage due to hazardous exposure to noise that could be sustained by an individual will be a function of (1) overall sound pressure level of the noise, (2) spectrum of the noise, (3) duration of exposure, (4) length of time between exposures and (5) the state of the person's hearing mechanism.

In a recent study of hearing of personnel on board one of the ships of the Royal Canadian Navy it was indicated that some of the men were experiencing temporary hearing losses of as much as 84% (American Medical Association per cent hearing loss formula) after being exposed for 2 hr to noise whose overall noise level was less than 122 dB (B1). It was further determined that approximately 180 hr of non-exposure was required before these men regained their normal thresholds of hearing.

Studies have shown that the sound pressure levels of noise generated by jet engines in engine-test cells at the National Research Council can be in excess of 140 dB (B17). In the control room, outside the engine-test cell, the overall noise level varies between 95 and 102 dB with the engines operating at maximum power. Personnel working in the control areas are generally exposed to these levels of noise from 3 to 4 hr per day during the testing periods. During the normal workday some of the personnel

are exposed, for brief periods to noise whose overall levels exceed 120 dB. However, during these hazardous exposures to noise personnel wear hearing protectors such as the Mine Safety Appliances Company ear-inserts (V-51R type) or a modified type of the Safety Supply Company ear-muffs (NRC type). Standard pure-tone audiometric tests were administered annually to the engine-test cell personnel for a period of six years. Analyses of the audiometric data indicated that, over this six-year period, the changes in hearing acuity of these men were non-significant.

HEARING CONSERVATION

The Sonics Section, Defence Research Medical Laboratories, has outlined a Hearing Conservation Program suitable for use by either the armed forces or civilian organizations (B18). This program is similar to the program prepared by the Sub-Committee on Noise in Industry, Committee on Conservation of Hearing, American Academy of Opthal-mology and Otolaryngology. The Hearing Conservation Program includes: (1) the measurement, and analysis of the noise stimuli; (2) the use of hearing protection criteria; (3) the use of pre-employment, periodic and post-employment audiometry; (4) the use of hearing protection devices and procedures; and (5) the conducting of an education program.

Noise measurements may be made in several different ways. The purpose for which this information is to be used will of course, determine the procedures carried out (B19). One procedure involves the measurement of the overall sound pressure level which gives an indication of the acoustic energy over a wide range of frequencies (usually 200–9600 cycles per second (c/s)). Another procedure often used is that of measuring the sound energy of the noise in frequency bands. The degree of frequency band resolution depends on the type of information required.

Hearing protection criteria for lifetime exposure to jet or propeller engine type noise have been prepared and if these criteria are followed most individuals should suffer no permanent hearing losses due to hazardous exposure to noise whose overall level is less than 150 dB (see Table B3).

The hearing-test program includes: (1) pre-employment pure-tone tests; (2) periodic tests, supplemented by periodic standard pure-tone tests where necessary, and (3) post-employment pure-tone tests. Calibrated manual or automatic audiometers may be used for standard screening tests. However manual audiometers should be used where a complete clinical evaluation of a person's hearing is required. All hearing tests should be carried out at least 48 hr after the time of the last exposure to noise.

Periodic hearing tests should be carried out on all personnel exposed to high-intensity noise. Such tests should include at least the frequencies

TABLE B3

Hearing protection criteria

Overall noise level (dB re: 0·0002 dyn/cm²)	Exposure time	Ear protection to be used *
85–100	Over 4 hr per day	Optimum ear-inserts *or* ear-muffs
100–130	Any	Optimum ear-inserts *or* ear-muffs
130–150	Any	Optimum ear-inserts *and* ear-muffs
150–	No exposure permitted	

2000 and 4000 c/s. Significant losses at either of these two frequencies should result in the person being given a standard pure-tone hearing test. A persistent change in hearing acuity of 15 dB at one or more frequencies should result in the individual being given a complete otological examination and being considered for transfer to a less noisy environment. Three complete pure-tone tests should be administered on different days before recommendations are made for the removal of an individual from his job.

All hearing tests, using calibrated manual or automatic audiometers, should be carried out in a suitable acoustical environment which will not cause a masking of the test tones.

Results of sound attenuation tests suggest that optimum ear-insert and ear-muff hearing protectors will provide adequate protection to the hearing mechanism if the overall level of the propeller or jet aircraft noise does not exceed 145–150 dB. The Mine Safety Appliance ear-insert protector (V51R type) provides the most effective noise attenuation for this type of protector. With proper fitting this device provides an average sound attenuation of 28 dB below 1000 c/s. The Safety Supply Company "Saf-T-Ear Muff" developed by Shaw and Thiessen at the National Research Council, Ottawa, Canada, is one of the most effective noise attenuators of this type of protector (B26). This device provides an average sound attenuation of 30 dB at frequencies below 1000 c/s. Above 1000 c/s the V51R type ear-insert provides an average sound attenuation of approximately 35 dB while the "Saf-T-Ear Muff" provides an average attenuation of approximately 43 dB. These types of ear protectors, which reduce the intensity of airborne vibrations through the external ear canal, have almost reached their maximum effectiveness. The level of bone-conducted sound, reaching the cochlea through the head, neck, chest and other parts of the body, is reduced approximately 40–50 dB depending upon frequency, from the level of air-conducted sound through the external

ear canal. The protection problem for those exposed to high-intensity noise whose overall level exceeds 150 dB is one of providing protection for the individual's whole body.

The aim of the education program should be to instruct personnel in the effects of high-intensity noise on hearing, its masking effects on voice communications and the methods by which personnel can minimize these effects. It should be stressed that the wearing of proper ear protection and the observance of correct noise protection procedures will result in the prevention of permanent hearing loss, reduction in pain, tiredness and irritability.

EFFECTS OF NOISE ON VOICE COMMUNICATIONS

Requirements for an adequate voice communication system include a noise-free environment for both the speaker and the listener, as well as (1) intelligible speech, (2) standard phraseologies, and (3) adequate speech-transmission characteristics of the audio equipment. A frequency range of from 300 to 6000 c/s is required for adequate transmission and reception of intelligible speech under adverse noise conditions.

A reduction in voice communication efficiency may be caused by an increase in overall noise levels which, without a similar increase in signal level, results in a negative signal-to-noise ratio, i.e. speech signal lower in Sound Pressure Level than noise. Increases in overall noise levels and a resultant increase in the masking of speech in a voice communication area may be due to: (1) number of men employed in the area; (2) number of messages transmitted or received; and (3) high gain settings of the intercommunication equipment which cause interference with other auditory signals. In addition, the lack of training in correct "speech listening" procedures; inefficient placement of intercommunication equipment (loudspeakers, microphones, etc.) and the incorrect type or improper use of intercommunication equipment may also decrease voice communication efficiency.

Recent studies have indicated that the addition of visual to auditory cues may raise the intelligibility of received speech, under adverse noise conditions, by at least 20% (B16). Television, speech reading (lip-reading) and hand signals can be used to increase the efficiency of communications for personnel working in high-intensity noise environments. The most efficient voice-communication equipment that we have to-day is not adequate for use in jet-engine noise environments when the overall level of the noise exceeds 130 dB.

Canadian research work has also included the study of the intelligibility of phonetic alphabet items at various altitudes under adverse noise conditions (B13). The results of these studies using Canadian speakers (who spoke with a General American dialect) and listeners, indicated (1) no significant differences in word-intelligibility between the ICAO I (Able, Baker, Charlie, . . ., etc.) and ICAO II (Alpha, Bravo, Charlie,

. . ., etc.) phonetic alphabets as a whole, (2) no significant differences in word intelligibility as regards position in a three-word phrase, and (3) a highly significant difference in word intelligibility as regards three altitude conditions (sea-level, 15,000 ft and 30,000 ft). There were, however, significant differences in the intelligibility of several of the alphabet items. These results, together with U.S. and U.K. results, were used as a basis for the development of the new Spelling Alphabet for International Radiotelephony. The new Spelling Alphabet includes the following items (B14):

A – Alfa	N – November
B – Bravo	O – Oscar
C – Charlie	P – Papa
D – Delta	Q – Quebec
E – Echo	R – Romeo
F – Foxtrot	S – Sierra
G – Golf	T – Tango
H – Hotel	U – Uniform
I – India	V – Victor
J – Juliet	W – Whiskey
K – Kilo	X – X-ray
L – Lima	Y – Yankee
M – Mike	Z – Zulu

Other studies have indicated that S.O.S. is a more efficient "alerting" signal than Mayday for radiotelephony (B15). Studies of the intelligibility of verbal digits indicate that in two, three, and four verbal digit sequences the digits 1, 4 and 6 are the most intelligible while the digits 2, 3 and 8 are the least intelligible (B23). The main digit confusions are 4 for 0; 2 for 3; 3 for 2; 3 for 8; and 6 for 8. Similarly it has been found, that, of the 26 verbal colour symbols studied, black, purple, indigo and oxblood were among the most intelligible words in two, three and four word phrases while slate, beige, cherry and rouge were the least intelligible (B24).

Results of other studies have indicated that hyperventilation, experienced for 15 min, produces a significant increase in the subjects' speech intelligibility (B25). The increase in speech intelligibility was produced primarily by an increase in the sound pressure level of the subjects' speech resulting in a more advantageous signal-to-noise ratio. At the same time there was a decrease in the precision with which the subjects articulated. This however, had little effect on their intelligibility. It was also determined that there was no change in the subjects' threshold of hearing for a 4000 c/s tone due to the hyperventilation condition.

FUTURE RESEARCH

Much more bio-acoustic research is urgently required. To this end Canadian investigations are planned which will provide some of the

required information. Future work will include studies to determine: (1) the mechanism and degree of human susceptibility to noise; (2) psychological and physiological tolerance thresholds for hazardous noise exposures; (3) the mechanism of temporary and permanent hearing losses due to hazardous exposures to noise; (4) the effects of high-intensity noise on human behavior; (5) the effects of intense acoustic energy on tissue and blood; (6) the development of standardized, intelligible phraseologies and procedures for radiotelephony; (7) the development of efficient methods for transmitting information in high-intensity noise environments, and (8) the development of adequate tests for evaluating the efficiency with which trained personnel with various types and degrees of hearing losses, can use radiotelephony.

SUMMARY

The overall levels and spectra of noise generated by modern aircraft are such as to cause temporary or permanent deafness, disruption of voice communications, changes in man's work-behavior and may elicit antagonistic responses from exposed personnel. The implementation of adequate programs of hearing conservation can provide protection to the hearing of individuals if the noise to which they are exposed does not exceed 150 dB. The use of standardized procedures and intelligible phraseologies in radiotelephony will aid in reducing errors in the transmission of voice information particularly in adverse noise environments. Noise whose overall levels exceed 130 dB makes the use of present-day voice communication equipment useless. However the use of visual cues and procedures will permit the transmission of certain types of information in noise environments where the overall noise level exceeds 130 dB.

Much more bio-acoustic research is urgently required to determine the temporary and permanent psychological and physiological effects of high-intensity noise on man and his behavior.

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