ADVANCES IN AEROACOUSTIC WINDTUNNEL TESTING TECHNIQUES FOR AIRCRAFT NOISE RESEARCH

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Abstract

Acoustic windtunnels with models mounted in a quiet test-section airstream surrounded by an anechoic working-chamber have now been established as primary tools for aircraft noise research work, and should be exploited for the direct support of specific quiet aircraft projects. During the past five years, the major problem areas associated with tunnel design and application for noise-model testing at subsonic speeds have been greatly clarified. Here, the special aeroacoustic techniques and limitations required are analysed and quantified, including tunnel test-section demands, tunnel-circuit and airflow-drive design, experimental measurement and analysis techniques, and engine/airframe noise simulation at model-scale. The discussion is based mainly on RAE experience in aeroacoustic testing techniques, particularly with reference to the development and exploitation of the 24 ft anechoic tunnel (7.3 m diam) and the new 1.5 m acoustic tunnel, while naturally taking into account known experimental and theoretical developments elsewhere.

1. Introduction

1.1 General Background

To ensure meaningful evaluation and prediction of configuration and flight effects on aircraft noise generation and propagation, reliable representation and measurement of relevant aerodynamic flow conditions as well as of acoustic characteristics must be possible(1). Acoustic windtunnels, with models mounted in a quiet test-section airstream surrounded by an anechoic working-chamber, have now been established as primary tools for noise-model research work and should next be exploited also for the direct support of specific quiet aircraft projects(2). The special advantages of such tunnels in ensuring a more sheltered and controlled environment than outdoor mobile-model facilities and flight-testing include capability and continuous operation, repeatable test conditions, high productivity, good measurement accuracy, testing flexibility, and the precise alleviation of reflections from neighbouring surfaces. Of course the recent experience on noise testing under forward-speed conditions and on associated techniques is still very limited at both model-scale and full-scale, as compared with extensive and continuous aerodynamic testing over half-a-century. However, many of the problem areas associated with subsonic tunnel design and application for noise-model testing, as identified over five years ago(3), have now been clarified. Also, the special treatments or limitations involved have become quantifiable in many respects, as discussed later under the convenient main headings of Tunnel test-section requirements (Section 2), Tunnel circuit design (Section 3), Special measurement and analysis techniques (Section 4) and Model-scale simulation (Section 5).

In particular various parasitic noise fields, which can be produced naturally by the testing environment and which could mask the true measurements of model noise (Fig 1) may be precluded or alleviated by applying and extending existing design experience in noise reduction and tunnel airflow control.

(1) Acoustic lining of the working-chamber can minimise reverberation effects down to acceptably low frequencies (Section 2.1); here an open-jet test-section with the working-chamber wall treatment well clear of the airstream offers distinct advantages over a closed test-section.

(2) Acoustic treatment of the tunnel circuit can reduce substantially the intrinsic background noise which could reach the tunnel test-section from the tunnel drive-fan and circuit (Sections 3.1 and 3.2); here a fan of low tip-speed located well remote from the test-section, in a low-speed duct region providing a high tunnel contraction-ratio, alleviates the penalty for adequate silencing (Section 3.4).

(3) Good quality mainstream flow into the test-section (Section 2.3) and the prevention of significant flow changes with powered-model condition helps to avoid spurious noise generation; the former requirement tends to favour a closed-circuit tunnel and the latter an open-return.

(4) Model rig and microphone arrangements should be carefully chosen and tailored to reduce their self-noise and local aeroacoustic interference in the airstream (Section 4.2); with an open test-section the far-field measurement microphones and supports can be located outside the test-section airstream, in nominally still air, but the effects of noise propagation across the airstream mixing boundary then have to be allowed for (Section 4.3).

For practical application to full-scale far-field conditions, reliable noise measurements should be achievable within the 'free-field' portion of the model-source far-field, where the sound-pressure-level varies inversely as the square of the distance (spherical radiation) apart from atmospheric attenuation. Since this 'free-field region' is bounded internally by the 'near-field region' of the noise source and externally by the 'reverberation-field' of the working-chamber, the maximum permissible size of model and the minimum permissible size of test-section are restricted from acoustic as well as aerodynamic considerations (Sections 2.1 and 2.2). Also a minimum acceptable size of model can be determined by practical difficulties in achieving adequate microphone response and resolution simultaneously with high frequency measurements, as well as from representative model construction problems at small-scale.

To relate the tunnel model experiments directly to conventional flight conditions, an analytic framework has to be specified for the appropriate frame-of-reference transformations. This must convert from the relative motions for the fixed model in the tunnel airstream with the microphones also fixed inside or outside the airstream, across to the moving aircraft in ambient still air with the microphone fixed on the ground (Fig 2, Section 4.1). Current practice is to correct tunnel measurements for the absence of elementary Doppler shift effects on sound frequency, for the presence of elementary airstream convection effects on sound directivity angle, and for simple refraction effects through the airstream mixing boundary if external microphone locations are employed (Fig 3 and 4, Section 4.3).

For adequate simulation at model-scale in tunnels or other facilities, the relevant geometrical and constructional features have to be selected for representation in relation to any aerodynamic, elastic and dynamic aspects particularly affecting noise generation, with overall consideration of scaling-factor implications. Some non-dimensional similarity parameters then have to attain values at model-scale reasonably close to those of interest full-scale; eg Mach number, Reynolds number, effective-speed ratios (blade-tip/airstream, or engine-flow/airstream), and Helmholtz number. Essentially, shortfall in some of the parameter values may have to be accepted in practice as of secondary importance, and interpreted in the light of experimental variations of the parameter values and other experience. At the same time, other scaling factors such as selected Strouhal number (frequency parameter) and sound-level coefficients should be validated experimentally as applicable to full-scale practical prediction for the particular aircraft type of interest, for example by comparisons at different model scales. Of major significance is the meaningful representation (qualitative and quantitative) of the full-scale noise sources and radiation characteristics from propulsive systems and adjacent surfaces, or from any powered-lift schemes. Fortunately, with careful appreciation of the specific research task, only partial simulation of the engine noise sources and engine airflow is needed for studies of the particular noise changes due to forward speed. Even so there remain significant problems including model-drive and model-support implications (Section 5).

1.2 Scope of Tunnel Testing Techniques

Several small acoustic windtunnels, with equivalent-area diameters of their test-sections less than 3 m, have now been developed world-wide to provide simultaneously both an anechoic working-chamber and lower background noise, either in the form of an entirely new facility or by modification of an existing aerodynamic tunnel. The provision of even smaller 'free-jet' acoustic tunnels, by simple adaptation of an existing anechoic chamber with capability of static noise-testing of jets, has also proved attractive; the major jet efflux of largest available diameter is employed as a mainstream flow, typically around a model-jet coaxially centred but of much smaller diameter. Some aerodynamic tunnels of small-to-medium size have also been given partial acoustic treatment, either around the test-section boundaries to reduce reverberation, or inside the tunnel circuit to reduce airborne transmission of drive-fan noise to the test-section. However, the need for much greater tunnel size from considerations of acoustic as well as aerodynamic constraints has required corresponding developments urgently in large tunnels.

The RAE 24 ft anechoic tunnel (Fig 7), with its open-jet test-section 7.3 m diam x 13 m length, max airspeed 50 m/s and closed return-circuit, now has its working-chamber boundaries 13 m width x 10 m height x 13 m length lined with sound-absorbing foam sheet and wedges to provide a cut-off frequency as low as 200 Hz. With such modifications, this 40-year old tunnel has been employed since 1971 for a variety of basic noise-model investigations and for the improvement of associated testing techniques. Nevertheless it must be stressed that, because of the present location of the drive-fan inside the collector immediately downstream of the test-section, the background noise can become excessive at airspeeds much above 30 m/s without the use of directional microphone techniques. The NASA Ames 40 ft x 80 ft tunnel, with its closed test-section 24 m x 12 m x 24 m length, maximum airspeed 95 m/s and closed return-circuit, has been employed for noise testing with very limited acoustic lining of the test-section boundaries and likewise without acoustic treatment of the internal circuit. Special microphone arrays and other interference correction techniques have therefore had to be introduced there to permit some discrimination against the reverberant-field and background-noise levels. The experience obtained in both these large tunnels has naturally stimulated proposals for their economic modernisation and has influenced the design specifications for new large tunnels, such as the German-Dutch DNW 8 m x 6 m tunnel presently under construction at the NLR (Netherlands, NE Polder) with interchangeable closed and open test-sections 8 m x 6 m x 18 m length and max airspeed 100 m/s.

The topics already identified in Section 1.1 are discussed here mainly in terms of RAE experience on aeroacoustic testing techniques, particularly by reference to our research towards the development(3) and the exploitation(1) of the 24 ft anechoic tunnel (Fig 7) and of the new 1.5 m acoustic tunnel (Fig 9). The latter has involved radical modification of an existing 5 ft diam open-jet tunnel (scale-model of 24 ft) in order to double the usable airspeed for noise-model testing, now 60 m/s. The external shape of the tunnel circuit was maintained as representative of the concrete-shell of the 24 ft tunnel, the existing low contraction-ratio was retained in order to avoid reduction of the test section size, a new low-noise fan was located in the return-circuit remote from the test-section (not in the collector), acoustic treatment and essential aerodynamic re-shaping were incorporated inside the tunnel-circuit, and a completely-closed anechoic working-chamber was provided around the test-section. More generally, directional acoustic receivers and other discrimination/correlation techniques are being applied to help the diagnosis of changes in noise-model characteristics with airspeed and the isolation of true model-noise propagation from unwanted parasitic noise. The development of noise models with better selective simulation of propulsor noise sources (under flight conditions) is also being attempted at RAE and NGTE, along with the formulation of better theoretical frameworks, especially to improve complementary interpretation of experimental results from small-scale models and full-scale engines in tunnel and in flight.

The present paper naturally offer the authors' analyses and interpretations, taking advantage of helpful discussions with colleagues, in particular T. B. Owen, W. J. Trebble and J. McKie at RAE. In addition, it also attempts to reflect the comments and opinions of some aeroacoustic specialists from North America and Europe, as expressed during discussions held under the auspices of AGARD(2) on ground-based facilities with forward-speed representation for aircraft noise research.

2. Tunnel Test-Section Requirements

2.1 Measurement Frequency Range and Model-Scale

Conventional absorber techniques can be employed in the anechoic design and application of windtunnel test-sections for aircraft noise research, though a variety of special testing requirements can then arise as discussed throughout this paper. As a rough working rule for the acoustic treatment of tunnel test-section boundaries, adequate absorption of incident sound energy can be achieved by foam sheet covering (thickness t) for wavelengths up to $\lambda_{max} \approx 2t$, or by foam wedges (height h) up to $\lambda_{max} \approx 5h$. Nevertheless in practice there can be significant regions which are not amenable to appropriate acoustic treatment for aerodynamic or structural reasons, including downstream or upstream facing areas in or at the ends of the test-section leg. For open-jet tunnels, an adequately anechoic test-section can be provided in principle without appreciable aerodynamic interference on the test-section airflow, simply by appropriate acoustic lining of the large working-chamber well clear of the open-jet boundaries. But acceptable treatment of the collector entry and of any supporting structure for the jet nozzle can be difficult. For closed-jet tunnels, the acoustic lining of the test-section tends to be more limited because the surface presented to the airflow has to be relatively smooth, streamlined and hard-wearing. The outer covering should preclude objectionable aerodynamic interference with the test-section airflow, or the generation of additional airflow noise, while not impairing the sound absorption efficiency of the particular scheme nor allowing deterioration due to long-period scrubbing effects.

These practical restrictions on the acoustic treatment of the test-section boundaries of open or closed-jet tunnels make some form of acoustic calibration essential, locating the calibration source and measurement microphones in positions representative of those envisaged for noise-model experiments. In general, such calibration will result in a defined test-region or volume within which the source free-field can be measured to sufficient accuracy, say $\pm\frac{1}{2}$ dB, in the presence of an acceptably low reverberant diffuse field arising from the boundary-reflected sound. Such an accuracy requires a separation of at least 10 dB between the direct and reverberant signal levels at the measurement positions. Available calibration techniques, as for anechoic rooms, include directed tone bursts, measurement of the far-field of a steady compact monopole source - the "inverse square law" test, and the measurement of the enclosure "early decay time" (EDT), which usefully can be defined as the time for an initial sound level to decay by 10 dB. All three of these techniques exhibit some complementary features and have been successfully applied to the acoustical assessment of the test-section of the RAE's 24 ft tunnel. In certain regions we have found, not unexpectedly, that a lower limit of about 1 kHz (rather than 200 Hz) can be imposed on the acceptable frequency range by the increase of reverberation in the present untreated return circuit as the measurement frequency in reduced, rather than by the corresponding decrease in the efficiency of the acoustic treatment of the working-chamber boundary.

The full-scale frequency range (F_{min} to F_{max}) of subjective interest for the prediction of perceived noise levels is typically from 50 Hz to 10 kHz. The lower limit on measurement frequency in model tests (f_{min}) is usually prescribed by the increasing difficulty of providing an adequately anechoic test-chamber at lower frequencies, though the problems are more tractable with an open test-section (cf closed) since the acoustic treatment of the solid boundaries (walls) is then far-removed from the test-section airflow. The upper frequency limit in model tests (f_{max}) is usually determined by the reductions in microphone size necessary to ensure adequate frequency response and spatial resolution at the higher frequencies, though with reduced signal strength, and by the problems of adequate allowance for atmospheric attenuation and directivity corrections with the higher frequency. Hence, to ensure an adequate frequency range at model-scale (length ℓ) of subjective interest at full-scale (length L), for appropriate correspondence at the same Mach number and same Strouhal number, the permissible model size is correspondingly limited in that

$$F_{min}/f_{min} > \ell/L > F_{max}/f_{max}.$$

Thus typically, with at best

$$f_{min} = 200 \text{ Hz} \quad \text{and} \quad f_{max} = 80 \text{ kHz}$$

$$1/4 > \ell/L > 1/8.$$

Such arguments are not intended to decry the usefulness of smaller-scale or larger-scale models, particularly over more limited ranges of frequency. But they serve to stress the importance of matching the model size and measurement frequency range to the capabilities of the particular anechoic chamber and of the available instrumentation, and the necessity for improvements in relevant instrumentation capabilities. More generally, the model size has to be made compatible also on a variety of other aeroacoustic counts, as discussed in the following sections.

2.2 Acoustic Wavelength and Geometrical Constraints

The extent of the near-field region from the noise model depends in general on the noise source type (monopole, dipole, quadrupole) and the intensity. But, for a compact source, it is roughly of the order of one or two wavelengths. Thus, to ensure that the acoustic far-field noise conditions (spherical radiation) are attained within the test-section airstream (radius R_{air}), the latter must extend to say at least 1.5 times the maximum wavelength λ_{max} ($\equiv a/f_{min}$) of interest from the model noise source. Moreover, to provide measurement conditions free of the boundary near-field interference effects, the measurement points should be at a distance (B_{mic}) more than say $0.3\ \lambda_{max}$ from any acoustically-treated wall or airstream 'free-jet' mixing boundary. Hence, as illustrated diagrammatically by Fig 5, for a centrally located compact noise source such acoustic wavelength constraints imply

$$R_{air} > 1.5 \times (a/f_{min}) \quad \text{and} \quad B_{mic} > 0.3\ (a/f_{min}).$$

The advantages of employing a large test-section are clearly evident from this aspect of permitting adequately long wavelengths (low frequencies), appropriate to large model size.

With practical models, as distinct from single compact noise sources, the finite geometry and character of the spatially large distribution of noise source elements across and along the tunnel airstream need to be allowed for, to ensure attainment of far-field measurements. For then, the extent of the near-field of the distributed noise source depends strongly not only on the wavelength (or frequency) of interest, but also on the relevant characteristic dimension of the noise source and the possible variation of predominant frequency and sound power along its extent. Indeed, the choice of characteristic dimension itself could vary with the frequency band and noise measurement direction of primary concern. Such model 'geometric' size constraints can be more significant than the 'wavelength' constraints of the preceding section. The formal specification of general working rules for predicting the near-field limits for practical noise models covering our interests is thus still difficult.

For an open-jet tunnel, with the test-section airstream surrounded by a much larger anechoic chamber, it could be argued that full development to such geometric far-field conditions need not be achieved until well outside the airstream jet-mixing boundary. Then, because of the alleviation on the foregoing constraint arguments, relatively larger models might be permitted; assuming of course that other acoustic wavelength constraints, aerodynamic constraints, and avoidance of distortion of the airstream boundary are not already limiting factors. Nevertheless, the use of microphone locations outside the airstream mixing boundary can introduce doubts concerning noise propagation characteristics across the varied and complex flow field between the model source and the microphone (Section 4.3), particularly if the source-noise characteristics are unknown or varied. Any increase in source signal strength from a larger model tends to be counterbalanced by the attenuation effects from the more distant measurement points required.

An important example arises in the application of a small 'free-jet' tunnel for testing of a model-jet coaxially-centred on the mainstream jet, with the need to achieve a model-scale as large as possible without excessive testing constraints. Here, from turbulent jet-flow development concepts and practical experience, it can be argued that the aeroacoustic interference of the mainstream-jet development on the model-jet source-noise generation is only negligible if the ratio of mainstream-jet diameter to model-jet diameter is at least 10. However, unless this diameter ratio is even much greater (> 50 say), far-field measurement will necessitate microphone locations well outside the mainstream rather than within. Then the noise-propagation corrections associated with refraction effects through the mainstream external mixing boundary can be substantial for realistic Mach numbers; see Section 4.3 and Fig 4. Additionally the problem becomes much more complex and the available corrections more questionable if the model-jet is inclined to the mainstream or off-centre, or if airframe installation/interaction effects are to be explored.

Thus, in any practical noise experiments, it is advisable to explore the sound field at different distances as well as different directions from the model, in order to establish that adequate far-field conditions have been reached at the measurement points to the standard of accuracy required. More specifically, further quantification of the type of constraints raised in this and the preceding section could now profitably follow from a declaration and critical analysis of relevant experimental and theoretical results, supplemented by some specially directed and carefully controlled explorations of noise fields during future model testing programmes in acoustically-treated tunnels. There is an urgent need for such reliable guidelines to expedite more profitable designs of models, facilities and experiments for investigating forward-speed effects on noise. Even static test results for elementary models (if precise) could help the formulation of useful working limits for far-field measurement locations under forward-speed conditions in the light also of reasonable theoretical concepts; typically from diagnostic field studies on small-scale models in large anechoic chambers.

2.3 Flow Quality Requirements

The desirability of good uniformity, steadiness, and low turbulence of the flow in the test-section airstream is already well established for aerodynamic-model testing. The possible significance of such flow quality considerations on noise-model testing, either directly or indirectly through the influence of resulting aerodynamic changes on model noise generation and propagation characteristics, still needs to be clarified and quantified. In particular, there appears to be little quantitative appreciation as yet of the influence of intensity and scale of the turbulence in the oncoming mainstream as regards noise generation at the model, except that the influence could be relatively small perhaps for a jet efflux but significant for a fan intake. Nevertheless, these aspects certainly cannot be ignored, not merely for fan-model noise, but also for airframe-model noise and engine installation effects, at least for small-scale models; ie when the aerodynamic flow field under the low Reynolds number conditions can vary appreciably with stream turbulence. The declaration and analysis of any existing relevant results is now badly needed, complemented by some exploratory noise measurements and related aerodynamic studies in existing tunnels with known variation of turbulence, particularly on fan-powered models.

Noise measurements employing a microphone inside the tunnel airstream (rather than outside) are frequently required for far-field studies as well as near-field, unavoidably so with closed-jet tunnels and usually with large open-jet tunnels (Section 4.2). However, with a very quiet tunnel, the background noise measured inside the airstream by a microphone (even when fitted with a nose-cone and pointed directly upstream) can still be largely due to the interaction of the airflow with the microphone rather than the true quiet-tunnel noise levels. More specifically, theoretical arguments suggest that if u' is the rms longitudinal velocity fluctuation and U the airflow mean velocity, then the rms momentum-pressure fluctuation associated with the turbulence should be $\rho U u'$, while the static-pressure fluctuation should be about $\frac{1}{2}\rho u'^2$. Some experimental measurements by T. B. Owen at RAE, for the rms pressure fluctuations p' recorded by a microphone facing directly upstream, are plotted in Fig 6 with $20 \log_{10}(p'/\rho U u')$ as a function of Strouhal number fD/U, where here D is the microphone nominal diameter. These confirm that the microphone alone (without nose-cone) measured $\rho U u'$ as expected over a major portion of the Strouhal number range; the fall-off in microphone response to the pressure fluctuations at high frequency is also in line with the reduction in scale of turbulence ($L \approx U/2\pi f$), as expected. However, when a nose-cone is fitted, the microphone does not measure $\frac{1}{2}\rho u'^2$ but a fraction of $\rho U u'$ depending on the Strouhal number, this fraction being dependent on nose-cone shape. Admittedly this apparent primary dependence on $\rho U u'$ does not in itself provide a clear physical explanation of the microphone response to turbulence, particularly since the spectra of lateral component v' are similar to those of u' in the experiments presently completed. Nevertheless, the practical significance of these and other unpublished results cannot be ignored in that turbulence levels below 0.2% seem essential for acoustic tunnels, if the turbulence induced signal at the microphone (with nose-cone) is to lie below the intrinsic low background noise of the tunnel.

Now for the practical achievement of high quality airflow in tunnel test-sections, closed-return circuit designs are usually preferred to open-return (straight-through) designs. Additionally, the closed circuit helps to isolate the tunnel testing from the nearby outside environment, thus precluding spurious changes in model test conditions due to ambient winds and external noise, while partially shielding the surrounding community from objectionable testing noise. However, for the avoidance of spurious noise generation by models (again particularly fans), it is equally important to ensure that no significant distortion of the test-section airstream can arise from possible persistence of the model wake/efflux or from circuit-flow interference round the closed-return. Fortunately modern circuit designs provide appreciable distance for the jet efflux to disperse before reaching the tunnel fan remote from the test-section (not immediately downstream), which should reduce recirculation effects; also slotting of the collector of open-jet tunnels should help reduce flow unsteadiness. Nevertheless, further tests are desirable to quantify the effects of high energy efflux inserted in the test-section, particularly if directed at a large angle to the airstream direction or well off-centre, when more severe distortion may make it necessary to devise a scheme to more rapidly diffuse or even remove the jet efflux.

3. Tunnel Circuit Design

3.1 Background Noise Generation

Typically, the background noise level in the tunnel test-section or working-chamber must be 10 dB or more below the model source noise, over the frequency range of interest at the measurement points, to ensure adequate resolution (within $\frac{1}{2}$ dB) of broadband spectra without reliance on special discriminatory techniques. To ensure that noise spectra and directivity patterns at model-scale can be reliably extrapolated to full-scale flight, the tunnel usable speeds should approach closely those for take-off and landing, eg at least 50 m/s (100 kn) and preferably up to 100 m/s (200 kn). Large-scale models are of course required for good aeroacoustic similarity and to preclude microphone measurement problems at high frequencies, but tunnel background noise tends to increase at lower frequencies and the test-section acoustic performance demands become increasingly difficult. Furthermore, it is worth recalling that the source noise levels available for measurement at acceptable microphone locations may not increase with greater model-scale, if far-field limitations at the correspondingly lower frequencies for similarity necessitate also correspondingly greater microphone distance from the source. The principal factors contributing to the background noise are included in Fig 1 as part of the interacting acoustic aerodynamic elements associated with model-noise measurement in windtunnels.

External ambient noise effects may warrant particular consideration in the design of open-return (straight-through) tunnels and for test-sections not protected by an acoustically-treated working-chamber. Structural transmission of mechanical vibration and motor noise from the tunnel-drive system may require special precautions, but problems can be avoided by heavily constructed and damped components with appropriate isolation joints. Minimisation of model-rig noise may need special attention when air has to be supplied to model jets and fans, or to resonance-type generators, since internal airflow noise from valves and pipework has to be avoided, along with externally-generated noise from possible vortex shedding and other aerodynamic interference by supporting structure/wires. Spurious noise can likewise be generated by measurement devices and their supports located in the airstream (Section 4.2), but the influence of turbulent airstream pressure fluctuations on the noise recorded by the microphone (Section 2.3) or of microphone support vibrations tends to be of more practical concern as setting the lower limit of background noise, especially in quiet anechoic tunnels.

The residual background noise elements, apart also from possible working-chamber boundary constraints on model-noise propagation (Section 2.2), may be considered to make up the intrinsic background noise associated with the tunnel-fan and circuit aerodynamics. In general, the design characteristics needed for a good aerodynamic tunnel with uniform low-turbulence flow in the test-section tend also to help towards providing a quiet tunnel by minimising unsteady separated flow conditions around the circuit and by careful aerodynamic design of the fan-in-duct combination. Again, for aerodynamic reasons, anti-turbulence screens and honeycombs are usually located in low-airspeed regions, so they need not create any significant self-noise problems with a reasonable tunnel contraction-ratio (say > 6). However, the possibility of embarrassing self-noise generation by other tunnel flow-control devices must be kept in mind; for example, essential turning vanes and support struts/wires in the circuit flow must be designed or damped to avoid intrusive noise due to 'singing'. Equally well, any inserts for acoustic treatment should neither promote significant self-noise in the flow (Section 3.4), nor introduce troublesome wakes.

In respect of choice of test-section type, with either free or walled boundaries at the edges of the airstream, the open-jet at first sight would appear the more attractive for low background noise levels. The noise emanating from the contraction nozzle and the collector/diffuser can then radiate freely (at least hemispherically out of the test-section) along with that from the model under test, without significant reflection from the acoustically-treated distant boundaries of the surrounding large working-chamber. In principle, the achievable lower limit to background noise may be expected to be set by the broadband quadrupole-type noise produced by the turbulent mixing at the free-jet boundary, for measurement points well within the airstream or several diameters outside. However, a special feature for most open-jet tunnels is the apparent need for 'tabs' protruding from the jet-nozzle periphery into the airstream, and/or venting of the collector by a cowl or wall slots, in order to preclude possible mainstream jet instability and low-frequency unsteadiness over the operational speed range (Section 3.3). For very quiet tunnels, aeroacoustic problems may then include possible excess noise and jet-boundary thickening from such tabs, collector noise from jet impingement and its possible variation with aerodynamic model testing condition, and adequate sound absorption treatment of the collector-entry/cowl still satisfying aerodynamic and structural needs. Correspondingly for closed test-sections, excess noise can be generated by the high-speed airflow over the test-section walls, especially with acceptable acoustic lining which itself may be of limited effectiveness because of other aerodynamic constraints, while other spurious noise and aeroacoustic constraints can be associated with the essential location of even the far-field microphones in the airstream.

The tunnel airflow-drive represents of course the primary source of background noise in the test-section, unless especially designed to have low noise characteristics (Section 3.2), and located far enough away from the test-section that sufficient circuit length is available in-between to permit adequate in-duct sound-absorption treatment (Section 3.4), with tolerable aerodynamic performance penalties. For example, the RAE 24 ft tunnel, which incorporates an old design of tunnel fan positioned at the collector end of the test-section (Fig 7) has its maximum usable speed (for an acceptable background noise level) restricted to below about 30 m/s for tests involving the practical noise sources associated, say, with the low velocity jets (Fig 8) and quiet fans typifying modern engines, while airframe noise is completely swamped at least in the far field. As expected for predominantly fan dipole-type sources, the overall sound pressure level of the background noise measured at off-centre positions inside the test-section decreases with distance from the fan. Also the overall sound pressure level increases almost as $(\text{airspeed})^6$ for the empty tunnel so that, in broad terms, each doubling (or halving) of tunnel speed corresponds to an increase (or decrease) of background noise by about 18 dB.

The radical modifications to the RAE 5 ft tunnel (scale-model of 24 ft), to provide the new 1.5 m acoustic tunnel, reduced the background noise SPL by about 15 dB over a wide frequency range (Fig 11), about half this reduction being attributed to the new fan design (Fig 10). A further reduction of the order of 5 to 10 dB still seems achievable, by changes in splitter surface design to reduce their self-noise, and by reducing the fan-blade angle in the tip region as a compromise more favourable to lower noise at the expense of overall aerodynamic efficiency. Much greater reductions are inhibited at this time by the requirement to maintain the low contraction-ratio (3.5/1) and the short circuit length relative to the test-section size, thus necessitating location of the acoustic splitters in regions of relatively high velocity and more severe fan performance requirements. Indeed the much smaller acoustic tunnel of effective diam 0.7 m built by UTRC(6) in the USA, with a much larger contraction from the inlet settling chamber to the test-section and correspondingly large diffusion thence into the extractor-type fan, provided SPL values outside the open-jet airstream as much as 40 dB lower than those for existing untreated tunnels when compared at the same airspeed and at the same Strouhal number. As regards acceptable standards of noise levels, representative powered models suitable for far-field noise experiments in the above acoustic tunnels can usefully be tested at airspeeds up to 50 m/s at least, without significant background noise problems and without the need for discriminatory techniques. However, under such conditions, spurious noise generated by the model-rig and in-flow model support (unless carefully streamlined) can augment noticeably the intrinsic background noise of the quiet tunnel and can also exceed the airframe self-noise from a clean unpowered model, all usually rising together with increase in airspeed whereas propulsor noise (eg from jet mixing) may simultaneously decrease.

3.2 Tunnel Airflow Drive

For subsonic tunnels, the conventional fan system with its well-developed continuously-running capabilities still tends to be preferred for the tunnel airflow drive; usually of an axial-fan type, though not always so for straight-through tunnels where other extractor-type fans can be conveniently exploited. The often contemplated air-injector drive may appear simpler than the fan drive, and probably cheaper if appropriate compressed-air supplies are already available on site. But, even if this pressure/induction system may be made as acceptably quiet as the fan drive, the limitations on running periods then available would often be unacceptable for general low-speed testing.

The tunnel fan itself can contribute a major component of the background noise level in the test-section, especially at low frequencies (Figs 8, 11). Consequently the fan design and the duct length available for acoustic treatment between the fan location and the test-section, both represent critical features as regards background noise limitations and acceptable airspeeds for any noise-model testing. The tunnel fan noise is mainly identifiable as of broadband dipole-type, usually attributed to lift fluctuations on the blades and associated with vortex shedding at the trailing edges. Typical experimental results are consistent with this, in that the fan sound pressure level tends to increase as the fifth to sixth power of the fan rotational speed. A useful crude working rule when comparing fans under similar operating conditions is:-

$$(\text{Fan overall sound power}) \propto (1 - \eta) \times (\text{Tip speed})^3 \times (\text{Aerodynamic Shaft-Power})$$

where, providing the fan aerodynamic efficiency $\eta\,[\equiv(\text{pressure-rise power})/(\text{shaft power})]$ is known, the inclusion of the aerodynamic power dissipation factor $(1 - \eta)$ offers a reasonable basis for comparing the noise of fans of differing design, since the aerodynamic losses and noise generation are closely related. The spectrum at a given rotational speed has a decreasing sound pressure level with rising frequency (eg Fig 8), but with discrete tones superimposed at the blade passing frequency and harmonics, whose intensities can be a function of inflow turbulence as well as tip-speed. Increase in inflow turbulence to the fan can also aggravate the broad-band noise.

For low noise, the fan should be designed to operate near the condition of maximum aerodynamic efficiency, avoiding significant flow separation regions on blades, but with a low tip-speed, say about one-third the speed of sound. Nevertheless, it must be appreciated that there can be a significant variation of airstream total head across the fan entry section, remaining sensibly axisymmetric if due to boundary effects in the test-section and duct upstream of the fan, but possibly with deviations due to non-axisymmetric acoustic treatments of the upstream ducts. Fortunately the well-designed single fan has proved a powerful and accommodating tool for providing a uniform distribution downstream of the drive section. With modern aerodynamic design methods, essentially involving the choice of an appropriate blade-twist distribution from fan-hub to tip for the expected velocity distribution into the fan and the required pressure rise through the fan, only small adjustments should have to be made to the predicted fan design after appropriate model fan-in-duct checks. Broadly speaking, a tunnel design which incorporates large contraction-ratio is favourable to low noise, because of resulting reductions in both the aerodynamic power required and fan tip speed, for a prescribed test-section size and speed. Now that several acoustic tunnel fans have been built to various quiet designs, including that by T. B. Owen for the RAE 1.5 m acoustic tunnel, experimental results on their aeroacoustic performance can be critically evaluated and compared for future guidance, before the construction of new larger tunnels or of new quiet fans for existing large tunnels. More generally, although continuous variation of tunnel speed is usually achieved through alteration of fan rpm, the fan aerodynamic efficiency and quietness could usefully be further improved (especially for large blockage changes) by incorporation of adjustable or variable blade angle, possibly even with some facility to adjust blade twist or effective camber at least during the installation proving stage.

3.3 Open-Jet Nozzle and Collector-Flow Interactions

In most subsonic tunnels, either with open or closed test-sections, careful tailoring of the test-section design as well as the tunnel circuit and airflow drive is invariably needed to ensure that the test-section flow is steady throughout the required airspeed range. Often, any shortfall or improvement in this respect is manifest also in the degree to which the allied requirements of minimum pressure gradients and minimum energy losses are met. Here, we are primarily concerned about possible low-frequency unsteadiness (pulsing) in open-jet tunnels, largely associated with interaction between the jet nozzle flow and the collector, which could generate excessive background noise and intolerable flow conditions. For preciseness, the primary origins of such flow unsteadiness (and appropriate treatments) can be divided into two different categories, though these can arise simultaneously.

Firstly, mixing at the tunnel airstream boundary, while traversing the space between the nozzle and the collector, results in entrainment of the order of 10% excess volume flow which has to be spilt at the collector entry. With the large-scale eddy sizes arising in this mixing, the instantaneous quantity to be spilt will show appreciable amplitude variations in the very low frequency range, so that tunnels with simple bellmouth collectors have experienced low-frequency variations in tunnel airspeed apparently associated with this unsteady entry flow. Most modern open-jet tunnels with closed-return circuits incorporate some form of ventilation slots downstream of the collector to accommodate this variable spillage and attenuate pressure waves which might otherwise propagate round the tunnel; in some cases extensive ad hoc tailoring of the slots has been required to obtain satisfactory tunnel flow, eg at DFVLR (Porz-Wahn) and VKI (Rhode-St-Genèse), while in other tunnels a single peripheral slot has given satisfactory results. Clearly, the aerodynamic design of the collector cowl has to be carefully tailored to the particular test-section and working-chamber configuration, while the cowl must also have acceptable structural and acoustic characteristics.

Secondly, nozzle/collector-edge-tones and related jet-flow oscillations are usually considered to originate from aerodynamic resonance between a disturbance (eg ring vortex) leaving the jet nozzle, impinging on the collector cowl, and then feeding back a new disturbance which arrives back at the nozzle in phase with the creation of another disturbance at the nozzle. The frequency of such edge-tones, (primary and higher-order) tend to increase with greater mean airspeed at the jet nozzle and then decrease with greater separation distance between the jet nozzle and collector. In some closed return-tunnels, severe vibrations of the tunnel structure have arisen when the jet/collector edge-tone frequency coincides with the organ-pipe resonance frequency of the tunnel duct. Two very different designs of windtunnels, the RAE 24 ft tunnel (also a fifth-scale model) with 3.5:1 contraction-ratio and the DFVLR Porz-Wahn tunnel with 10:1 contraction ratio experienced these severe organ-pipe resonances; while other tunnels of intermediate design, eg the model of the new DNW tunnel with 9:1 contraction ratio, apparently show no signs of this phenomenon. Fortunately when it does occur, this type of aerodynamic resonance can be readily suppressed or reduced by the introduction of peripheral tabs in the form of spoilers or discrete vortex generators at the nozzle outlet, to preclude regular formation of the jet ring vortices; but there can be some penalty because of possible increases in high frequency noise. It should be noted that in some cases (eg DFVLR Porz-Wahn) venting of the collector alone produced no noticeable attenuation of these organ pipe resonances.

Additionally, with the introduction of sealed anechoic chambers surrounding an open test-section, an alternative type of edge-tone resonance appears possible involving low-frequency standing waves in the chamber, rather than a return-circuit organ-pipe resonance. This supplementary type was apparently present in the UTRC Acoustic Tunnel (open return circuit), there again cured by the use of peripheral tabs, and was probably responsible for initial resonance problems in the NSRDC tunnel but there cured by collector slotting.

In view of the wide variations in severity of the unsteadiness problems reported in different open-jet tunnels, and the large variety of collector cowl shapes and venting configurations employed, more basic research would still seem worthwhile to further clarify the fundamental causes of the various types of unsteady phenomena and to provide detailed guidance for their avoidance in acoustic tunnels with minimum penalties in other respects. More generally, for dynamic as well as noise testing in open-jet tunnels, it seems essential to establish whether the test-section airflow can really be guaranteed to be as steady as that in good closed test-section tunnels, or whether some low-frequency unsteadiness and relatively higher levels of turbulence will remain despite jet-nozzle and collector treatments. The aerodynamic and acoustic significance of deflection of the open-jet boundary due to the presence of lifting models, particularly with powered high-lift systems, needs also to be explored further.

3.4 Noise Absorption Treatment of Tunnel Circuit and Aerodynamic Implications

Significant unknowns and restraints can arise in attempts to apply, efficiently and economically, sound-absorption techniques to substantially reduce tunnel background noise; by internal-circuit treatments between the drive-fan and the test-section. Some compromises in wall-lining and splitter designs are essential because of the following factors. Broadly speaking the absorption of high-frequency noise requires closely-spaced splitters, whereas low-frequency absorption demands greater lengths; also longer splitters at downstream positions from the fan than for upstream positions may be required to allow for sound convection effects(3). Local airspeeds and airstream-pressure losses tend to rise with silencing efficiency over a wide range of frequency, because of the more extensive circuit-flow blockage and larger wetted areas, even with careful streamlining. Low airstream-pressure losses are needed to ensure high airspeeds in the test-section with acceptable power and cooling requirements. Objectionable self-noise and reductions in absorption efficiency can be caused by high-speed airflow over the absorber surface areas. Reductions of absorber efficiency may be associated with the needs for surface protective covering and structural integrity in high-speed airflows without costly maintenance over a period of several years. Such considerations suggest that the most favourable tunnel-circuit locations for the application of sound-absorption techniques are where the airspeed is near the minimum, ie in the settling chamber upstream of the contraction and after considerable diffusion well downstream of the test-section, commensurate of course with the fan location, and with the circuit type and geometry.

Thus the elaborate NSRDC tunnel(5) incorporates long 'acoustic mufflers' in the especially large legs of the closed-return circuit immediately upstream and downstream of the quiet axial-fan drive, to reduce fan noise reaching the test-section particularly in the low-frequency range, but with only minor aerodynamic penalties. Each muffler comprises two sinuous absorptive splitters mounted vertically in the middle of the tunnel and one along each side-wall; the sinuous bends have a large radius to avoid flow separation, while providing additional high-frequency noise reduction by eliminating an unobstructed linear sound path through the muffler, and also increasing the effective length of the passage for a given geometric length of muffler. The aerodynamic total-head losses for each muffler were only about 15% of the overall loss round the tunnel circuit and about the same as the loss through the cooler or through the anti-turbulence screen section. Moreover, the perforated metal coverings of the absorptive material here causes no troublesome self-noise because the duct airspeed at these muffler locations is so low.

The simpler and smaller UTRC tunnel(6), with its open-return design and extractor-type centrifugal fan at the exit, avoids the need for acoustic treatment of the tunnel inlet upstream of the test-section but assuming of course the absence of any external noise problems. Downstream of the test-section, at the end of the conventional straight diffuser and just ahead of the drive-fan, the tunnel circuit incorporates a Z-shaped muffler (absorptive and reactive) comprising two arrays of parallel baffles/splitters and two lined 90^{o}-bends, which serve to attenuate the fan noise by at least 50 dB for frequencies down to 250 Hz in the test-section. Turning vanes were here not installed in the bends, to preclude the possibility of discrete frequency noise due to 'singing' and of broadband noise generation due to their immersion in turbulent flow from the diffuser.

However, for acoustic treatment of existing aerodynamic tunnels, or for the design of new dual-purpose tunnels where aerodynamic testing still has equal or greater priority than noise testing, other conflicting technical aspects and economic constraints can be limiting factors. The recommended practical modification of the RAE 24 ft tunnel (as Fig 9), maintaining the large test-section size (7.3 m diam) with the low contraction ratio (3.5/1), has uniform blocks of low-frequency and high-frequency splitters as part of the multi-passage diffuser downstream of the new fan, with similar blocks incorporated in the first diffuser just downstream of the collector primarily because a sufficient straight-length (upstream of the fan) is available only there. Then, since the circuit airspeed is high in the first diffuser, splitter self-noise becomes a serious design factor as well as splitter aerodynamic drag. The possibility of making the splitters sinusoidal along their length, to achieve increased sound attenuation by elimination of 'line-of-sight' through the block, is precluded here by lack of length when adapting this existing facility. Other designs for the modified RAE 24 ft, accepting a smaller test-section, provide not only a worthwhile increase in contraction-ratio and thereby improvements in top-speed and flow quality, but also inherently reduce the mean duct speed and required fan tip-speed for a prescribed test-section speed. So fan-generated noise and splitter self-noise then tend to be correspondingly lower, alleviating the acoustic absorption required to achieve the prescribed background noise in the test-section. It also becomes more attractive to take full advantage of the changes in direction through the circuit corners, by incorporating absorptive lining in the local wall surfaces and corner vanes.

Estimates of the acoustic properties of feasible splitter arrangements can be attempted using developments of Cremer's theory reported by Beranek and Schultz(9), where the splitters are considered to be of homogeneous porous material, with the acoustical impedance assumed to be a unique function of the through-flow resistance R_1 (Rayls/m) of the material. With the splitter thickness defined as 2t (m) and the gap as 2h (m) between the splitters, the maximum attenuation per unit length is then attained at a particular frequency $f_{opt} = 101.6/\sqrt{ht}$ (Hz), using an absorbent material with the 'optimum' flow resistance $R_{opt} = 667.5\sqrt{h/t^3}$ (Rayls/m). This peak optimum design restricts significant noise attenuation to only a narrow band of frequencies, but attenuation over a much wider band of frequencies can be obtained at the expense of a lower value of peak attenuation, if material with a higher flow resistance is chosen. Of course maximum attenuation for a given splitter length is obtained by making h small, but the airflow blockage can produce excessive drag losses, so that $h > t$ proves an essential compromise between the acoustic and aerodynamic requirements, with some lengthening of the splitters to compensate for the reduced attenuation per unit length. Some experiments by W. J. Trebble in the new 1.5 m acoustic tunnel at RAE have shown that the measured attenuation of sound through the low-frequency (LF) splitters under still air conditions (fan-off, loudspeaker noise source) is substantially less than the theoretical estimates except at low frequencies (Fig 13). Moreover, as regards drive-fan noise (with tunnel airstream flow), the effective attenuation provided by the LF splitters located in the collector is only of the order of one-half that expected from the still-air calibration measurements. Furthermore the addition of high-frequency HF splitters in the collector would actually increase the tunnel test-section background noise for all practical airspeeds, largely because of the self-noise of the closely-spaced HF splitters, located there of necessity in a region of relatively high velocity. Some schemes to reduce such self-noise, by modifications to the splitter surfaces without significant degradation of their true acoustic absorption performance, are now being explored. Also, possible residual transmission of drive-fan noise along paths external to the tunnel airstream needs to be checked.

4. Measurement and Analysis Techniques

4.1 Relative-Motion Considerations for Tunnel-Flight Correspondence

There exists an elementary direct correspondence between noise measurements for the model fixed in an ideal tunnel airstream (effectively uniform and unbounded) and for the same model in steady level flight at the same relative velocity to the likewise ideal still air, choosing for comparative purposes here a frame of reference fixed to a noise-model (Fig 2). Naturally for such ideal model test conditions in tunnel and flight, with the identical relative airflow velocity, measurements can directly correspond at the same microphone distance from the model, for the same sound emission angle θ (ie wavefront-normal inclination) to the direction of relative motion; there is then identity also of the 'retarded-time' from pulse emission at the model source to pulse reception at the microphone location. This careful distinction here between correlation of results from different test methods at the same value of the emission angle θ rather than of the 'convected-ray reception angle' ψ, while seemingly trivial at first sight, becomes of vital practical significance for the meaningful comparison and physical interpretation of some results at different flight and/or tunnel Mach numbers M and under static rig conditions.

In terms of simple convection arguments (Fig 2) for a uniform relative-airstream past a compact noise-source,

$$\tan\psi = \tan\theta(1 + M\sec\theta)^{-1}$$

For real flight, this emission angle θ is then the instantaneous line-of-sight angle from the distant stationary observer to the aircraft (ie flight model) at the sound pulse emission time; as distinct from the reception angle ψ which represents the instantaneous line-of-sight angle at the corresponding pulse reception time, varying with M even for constant source emission characteristics. In real tunnel tests, if desired to ensure measurements for unchanged values of emission angle θ as tunnel airspeed is varied (including static conditions), the datum microphone locations (ψ values for assigned θ values) can be displaced geometrically downstream with increasing airstream Mach number, according to the foregoing convection relationship. With an extensive distributed source (eg jet efflux) the geometric far-field conditions may not be adequately achieved for the allowable microphone distance from the model, when strictly these angles should be related to several equivalent source elements in turn rather than to the model geometrical location. Some rough checks, with simple source distributions based on theoretical arguments and other experiments (eg static), could usefully indicate the magnitude of possible errors due to the more convenient assumption of a single compact source at or near the model; see also Section 2.2.

To complete fully the practical equivalence at a prescribed airspeed Ma (Fig 2), the microphone should not only occupy the same position relative to the model frame-of-reference at pulse reception time (ie identical θ), but ideally the velocity of the microphone relative to the model should also be unchanged. Now in principle, for the same θ, the acoustic pressure amplitude measured by a moving microphone is independent of its velocity relative to the source, though any pulse is then detected over a time period proportional to $(1 + M \cos \theta)$. Hence in practical terms, the stationary microphone with stationary model in the tunnel airstream measures the same proportional-bandwidth mean-square pressures (eg third-octave) as the stationary microphone (conventional observer) with flight model (moving aircraft); strictly provided the tunnel airstream and flight Mach numbers are identical, for the same values of θ, and at the same microphone distance. Even so the tunnel-mode frequencies then need to be multiplied by the Doppler factor

$$(1 + M \cos \theta)^{-1}$$

to convert to the flight-model observer conditions with the separation speed Ma. More generally, to allow for essential differences in practice between the tunnel model microphone and the flight model observer distances, it is customary to appeal of course to the far-field inverse-square law, with $\Delta SPL \approx -6$ dB per doubling of distance. Additionally conventional corrections to allow for atmospheric attenuation may be applied, typically

$$\Delta SPL \approx -f/1000 \text{ dB per 150 m distance.}$$

Simple practical application of the foregoing emission-angle concepts, to expedite fundamental interpretation of the influence of different airspeeds (including static tests) on aircraft noise characteristics, implies not only assumption of a distribution of compact equivalent source elements (eg from mixing of a thin jet), but also free-field propagation in a uniform relative airstream (outside the jet boundary). Additional near-field effects, such as those attributable to airframe interference (eg shielding, diffraction, scattering) and to the aircraft flow-field (eg refraction through vortices) would then have to be included inherently as part of the equivalent-source distribution. Thus when the fundamental interpretation of the influence of airframe geometry and its local flow field on the noise propagation from a <u>known</u> source are of primary interest, it seems more realistic and meaningful to analyse measurements from low-speed tunnel tests at preferred inclinations of the source-microphone direction (reception angle), without prior adjustments to achieve 'nominal' prescribed values for the emission angle at source. This procedure is now supported by recent theoretical transformation arguments from K. Taylor(10) at RAE, which favour the use of a coordinate system fixed relative to the aircraft, but assume potential flow at low airspeeds ($M \to 0$) past an aircraft incorporating a known compact noise source. More generally, the foregoing discussion serves to stress the importance of comparing flight and tunnel tests at the same Mach number, and of exposing further the risks involved in interpretation from static tests.

4.2 Microphones Inside Tunnel Airstream

A preference for microphone locations well inside the test-section airstream of a large open-jet tunnel, as well as inevitably for closed-jet tunnels, can follow from the need to make noise measurements as close to the noise source as far-field requirements may permit (Sections 2.1 and 2.2), or as near-field studies will require. Simultaneously, the effects of parasitic flow fields at or outside the mainstream jet boundary, ie other than those flows properly associated with the model condition, are then avoided on the model noise propagation characteristics. To reduce the wind-generated noise at the microphone located within the tunnel airstream, for much higher airspeeds than conventional ambient-wind conditions, a streamlined nose-cone with a circumferential axi-symmetric strip of fine wire mesh is usually substituted for the standard flat grid protecting the microphone diaphragm, replacing also the conventional spherical porous windscreen. The nose-cone and hence the axis of the microphone diaphragm are pointed directly upstream at any microphone location to minimise airflow disturbances. The microphone response correction needed to give true free-field conditions is a complicated function of both the sound frequency and sound incidence at the microphone. Additional free-field corrections for the presence of the nose-cone are often determined by datum microphone measurements made with and without nose-cone, for noise generated by the model at <u>zero</u> tunnel airspeed. Fortunately the omni-directional characteristics of the microphone tend to be improved by the addition of the nose-cone, though sound incidence effects are still large at high frequencies and calibration checks are still essential. There is also some justification for the expedient practical assumption that the local airflow over the microphone in the tunnel airstream does not significantly alter the microphone response to the sound received, with of course the nose-cone and streamlined support kept aligned along the local airstream direction. Nevertheless, such microphone response and incidence corrections for in-flow measurements warrant further investigation, particularly with the need for more reliable measurements at higher frequencies.

The future significance of any residual wind-generated noise at microphones located within the airstream of open-jet tunnels or closed-jet tunnels also needs continually to be re-assessed, taking into account possible reductions in (or discrimination from) other parasitic noises, and the signal strengths of future interest from quieter or more complex model-sources. Recent experiments by T. B. Owen at RAE have confirmed that, unless very low turbulence levels are achieved, the pressure fluctuations associated with the turbulence in the airstream can determine the 'apparent' background noise levels of quiet tunnels, as indicated by a microphone (even with nose-cone) in the airstream. Indeed datum microphone measurements inside a very quiet small tunnel, but for very high turbulence levels (airstream u'/U of order 1% rather than conventional 0.1%), recorded SPL values as much as 20 dB higher than measurements well outside the airstream. Some further comments on this aspect can be found in the discussion of 'Tunnel flow quality requirements' (Section 2.3). Some recent advances made in both Europe and North America on the design of microphone probes for industrial sound measurements in turbulent duct flows are of interest; but may not be generally applicable for our purposes where large variations arise in the angular difference between the local-airflow incidence and predominant sound-ray incidence at the probe.

4.3 Microphones Outside Tunnel Airstream

With an open-jet test-section inside a much larger acoustically-treated working-chamber, the microphones for far-field measurements can alternatively be located external to the airstream and well clear of the mixing boundary (Fig 3) so as to be in nominally still air, though at a greater distance from the noise source giving a correspondingly weaker signal strength relative to the background noise level. Moreover, possible falsification of the noise measurements needs to be assessed and allowed for, because of the intervention of the mixing boundary between the noise source (within the test-section potential core) and the external microphones.

As regards spurious refraction of sound propagated through the mixing boundary, and even possibly through weaker secondary flow regimes outside the mixing boundary, early studies indicated that such effects were tolerably small and adequately assessable by qualitative ray theory arguments, for the low airstream speeds ($M < 0.15$) then feasible with acceptable background noise levels. More precise theoretical treatments have now been formulated by Amiet(8), Jacques and others, in which the tunnel mixing boundary is modelled simply in terms of a vortex sheet of small thickness (compared with the incident-sound wavelength) between the uniform stream and still air, without change in density across the shear layer (Fig 3). Essentially Amiet considers a plane interface and uses ray theory to derive equations which, conveniently for our purpose, permit sound pressure measurements p_m made at an apparent directivity angle θ_m and radius r to be corrected in both intensity and angle for 'ideal tunnel' conditions with the microphone immersed in an infinitely large airstream. The effect of the refraction is not merely to change the ray direction from θ_c' inside to θ_c outside the airstream (Fig 4), but also the intensity through effective changes in ray spreading angle as well as distance. The predicted changes to corrected angle θ_c' from visual measurement angle θ_m, and the corresponding changes in $20 \log_{10}(p_c/p_m)$ for an equal radial distance r from the source, are certainly no longer small when the airstream Mach number is increased from 0.1 to 0.3 (and to 0.5) for $h/r = 0.15$, where h is the separation distance between the source and shear layer. With increasing M, θ_c' essentially reduces over the whole measurement angle range, while the SPL at equal radius increases over the whole of the forward arc (upstream of source) but decreases over most of the rearward arc. Also, it should be noted that small angles to the airstream direction are not allowable in practice for measurements outside the airflow, because of the rapid variations in the corrections there, both in the forward and rear arcs; in the forward arc even at angles somewhat exceeding those for total internal reflection from the mixing boundary (ie even outside the 'zone of silence').

Additionally, the model noise propagation may be subject to frequency and spatial scattering at the test-section mixing boundary, or can augment noise generation from the turbulent mixing itself. Early experiments again implied that the practical effects were small, at least up to the maximum frequency of 10 kHz and for low airstream Mach numbers ($M < 0.15$) then tested. But such scattering effects are envisaged primarily as high frequency phenomena, affecting sound propagation at wavelengths less than the turbulence length scales within the mixing region. Indeed, for $M \approx 0.2$, noticeable broadening of a pure tone at about 24 kHz has been displayed by measurements made well outside the mixing boundary of the UTRC tunnel, while as much as half the transmitted intensity across a shear layer at very small wavelengths has been attributed to scattered waves from experiments by ONERA.

Overall, the complex nature and larger thickness of the mixing boundary needs to be properly appreciated in practical terms, including the influence of any tabs incorporated round the tunnel nozzle periphery to ensure airflow stability, so that representation by simple thin shear layers seems only an expedient gross approximation to the true airflow conditions. At this stage, the available theories and limited measurements should be used for qualitative guidance rather than precise corrections, preferably towards defining the test conditions for acceptably small corrections on the noise changes with forward speed under investigation.

5. Model-Scale Simulation of Propulsion and Powered-Lift Noise Sources

5.1 General Objectives

For clarification of relevant in-flight conditions, selective representation of the primary noise contributions from engine operation is required including engine-airframe interactions, with particular emphasis here on the possible changes in source noise generation and propagation characteristics resulting from the addition of the relative external airflow. Complete aeroacoustic simulation of a practical engine at model-scale is hardly feasible (Fig 14), nor is it necessarily desirable for research aimed towards clarification and evaluation of individual major noise components and possible alleviation. For example, it has already proved both expedient and profitable to simulate separately such specific noise generators of interest as nozzle with jet efflux and fan with intake under forward-speed as well as static conditions. Further engine-components of interest for simulation as 'internal' noise generators include other turbo-machinery (compressors and turbines) and combustion systems, while noise reduction devices and airframe interference also need to be represented. For completeness, it should be appreciated that many of the difficulties now raised in respect of model-scale simulation and relevant rig features apply not only to windtunnel facilities ('fixed'-model), but often even more acutely to mobile facilities, and particularly if equally reliable results are required.

The relative airstream effects to be expected, even for studies of noise from a particular engine-component, are not simple. They can comprise:-

(1) Changes in the source noise characteristics arising from the different local airflow and neighbouring surface areas, both internal and external to the engine-nacelle duct.

(2) Modified acoustic near-field development through the local flow field or from local airframe installation interference; including refraction, diffraction, reflection, absorption, scattering and possibly augmentation in the vicinity of the nacelle installation.

(3) Unpredictable development from the acoustic near-field to the aircraft noise far-field, again particularly across practical non-uniform airflow regions or solid surface areas, and with extended sources of a complex nature.

Fortunately, if acoustic and aerodynamic behaviour of the engine-component under static conditions is well understood or can be thoroughly explored, only partial simulation at model-scale may be needed for comparative studies of the primary changes due to forward speed, including the clarification and formulation of basic prediction methods.

5.2 Noise Sources Independent of Tunnel Airstream

Special noise generators whose sound emission characteristics at source are unaffected when placed in an airstream (or change in a known manner) can be profitably applied from at least two aspects, for noise tests in most facilities. Firstly, the validity of conventional or novel noise measurement techniques can be checked when employed within or outside the tunnel airstream, or with a mobile model. Secondly, the particular influence of neighbouring surfaces (eg shields) or of flow velocity gradients (eg vortex refraction), affecting the near-field and far-field propagation in the relative airstream, can be isolated and diagnosed more readily without simultaneous unknown changes at the source due to the airstream. Some electrodynamic noise sources, (eg loudspeakers), jet-resonators (eg Hartmann-type), and sirens have already proved useful and are being further developed for such work, particularly with a view to improving their performance in respect of power and frequency range, and to permit controlled variation of their directivity characteristics. However, for acceptable installations in close proximity to surfaces, inside or outside engine nacelles, more compact sources are needed avoiding significant aerodynamic interference on the local airflow.

5.3 Jet-Efflux Representation and Quiet Airfeed

Aero-engine jet-efflux development and the associated external jet-mixing noise-source distributions can be investigated at model scale, in principle simply by a geometrically similar jet nozzle, with an appropriate airfeed arrangement providing a quiet air supply to the model (negligible internally-generated rig noise) and an acceptable jet-flow profile. For static testing, this now usually presents a straightforward tailoring problem for the particular experimental configuration, involving the incorporation of a silencer, burners or heaters, plenum chamber, and substantial contraction often in close proximity to the nozzle. However, when forward-speed representation is required, such bulky bluff rigs become unacceptable because of their spurious aerodynamic and acoustic effects arising from their interaction with the external airstream. The introduction of conventional aerodynamic fairings to streamline or shield the rig in the airstream can generate its own problems (acoustic, aerodynamic and mechanical), particularly because of the relatively large sizes involved. Such rig problems are naturally tending to become more acute with advances beyond isolated single cold-jet models. Previous experience with jet aerodynamic testing in windtunnels is helpful, but alone is completely inadequate for noise-model and airfeed rig design, since good aerodynamic and acoustic simulation is simultaneously required without the introduction of parasitic noise sources. For example, while compactness of the external airfeed arrangement can be achieved in aerodynamic testing by very high pressure airfeeds to the jet nacelle, the controlled expansion (with pressure drop and turning) inside the nacelle to provide a representative flow at the nozzle must now not generate unwanted noise internally, or such excess noise must be controlled by internal absorptive treatment. The difficulties become aggravated with the demand for typical nacelle installations, heated jets, and coaxial or multiple jet arrangements.

5.4 Combustion Simulation Needs

The combustion system, in addition to producing steady-state temperature effects, can generate noise in at least three other ways; directly from the combustion processes, from interaction with the turbine systems downstream, and from interaction with the jet flow. For noise shielding investigations, the first two types (internally-generated noise) may be simulated crudely by incorporating prescribed noise sources within the feed-pipe, for example from internal loudspeakers, a jet hitting a target plate, or even multiple air injectors. But further investigations seem necessary to develop other more suitable devices for installation near to or within model nacelles. The third type, involving essentially the interaction of the unsteady combustion processes with the jet development, probably can be simulated adequately only by producing representative unsteady temperatures in the flow from actual combustion within the model. If this noise generating mechanism is indeed of practical significance, then careful investigations are required to guarantee reliable and controllable simulation of such source characteristics, particularly since external airflow can also affect the characteristics simultaneously.

5.5 Fan Representation and Quiet Drive

Aero-engine ducted-fan representation by small-scale powered-nacelle units generally cannot be expected to offer direct simulation and prediction of full-scale noise levels under forward-speed conditions, in respect of relevant discrete-tones and broadband spectra. For engineering reasons, some important full-scale geometric features such as the number of rotor and stator blades may not easily be duplicated at small scale, the boundary-layer flow characteristics over the duct walls and the blades can be unrepresentative at the low Reynolds numbers, and even the inlet-flow turbulence can differ significantly in intensity and relative length. Nevertheless, such models can be useful at least for diagnostic studies and design guidance, particularly in respect of specific model-configuration changes for which results can be interpreted using theoretical frameworks and thereby applied to estimate the corresponding influence full-scale. The required experimental measurements can then necessitate not only the incorporation of a relatively quiet fan drive, but also the ability to make both acoustic-pressure and aerodynamic-flow studies inside as well as outside the powered nacelle. Separately from noise-source generation considerations, the engine-nacelle flow characteristics and geometrical shape can of course affect the near-field acoustic development in the forward and rear arcs. In principle, for the investigation of such effects, simple high-frequency noise sources of broadband or discrete-tone types can be located within a representative nacelle-duct flow, with the location and directionality characteristics biased as appropriate; naturally, the influence of any variation in duct flow on the noise-source properties must be appreciated. Again, a combination of complementary experimental and theoretical modelling on particular noise aspects is especially important here for analysis of model-scale results and relevant full-scale interpretation.

5.6 Scaling of Noise Reduction Devices

Noise reduction devices which influence primarily the acoustic propagation towards the measurement point, rather than effecting reduction of sound energy or other changes in characteristics at source, can be subdivided conveniently here into noise absorbers and noise shields. Dissipative-type absorbers whose acoustical performance is determined mainly by viscous flow resistance can often be simply scaled, though the levels of accuracy achievable in the presence of different airflows and at very small scale are not clear, particularly if substantial protective covering has also to be simulated. Resonant-type absorbers currently in use, with perforated sheet facing, are especially subject to significant Reynolds number effects, and it has been suggested that model scaling down below about one-third full-scale requires very careful justification. Indeed, some lack of confidence has been expressed in the practical usefulness of modelling liners in engine ducts at well below full-scale and without detailed engine component representation, for other than basic comparative tests. Shield-type devices usually need to be several wavelengths in size to be effective, so tend to be reasonably large and in principle can be readily modelled if the noise source frequencies are also properly scaled. However, the possible interactions of any aerodynamic flow field with the acoustic field and shield have to be taken into account; in particular the shield boundary conditions should be adequately represented at the shield trailing-edge or the effect of possible variations investigated. Thus, further research on how to model absorption treatment of airframe surfaces and special shields does seem justified, taking note also of the airframe/engine interference considerations referred to next.

5.7 Airframe Interference Representation

The airframe, apart from providing direct shielding or absorption/reflection properties, can also affect the engine noise characteristics by aerodynamic interactions with the exhaust or inlet flows, and by influencing the acoustic near-field development. Correspondingly, engine airflow in the vicinity of airframe surfaces or edges can introduce excess noise from the airframe (even statically). The external airstream associated with flight conditions may radically modify these interaction effects and the ensuing noise propagation, while simultaneously generating noise from the airframe which can be significant with landing devices deployed and quiet engine conditions. Here again, the complexities of the related acoustic and aerodynamic effects are so marked that careful selective modelling from both aspects is essential with realistic and well-defined goals. Because of the small amount of experience yet accumulated, any flight research on aircraft noise should invariably be complemented by appropriate model tests, to take full advantage of the possible correlation and clarification of experimental results and the mutual improvement of measuring and analysis techniques. Such complementary experimental programmes have now been undertaken in the UK and USA at least. Moreover, NASA Ames have attempted with some success a few direct tunnel-flight comparisons on small full-scale aircraft, even though handicapped by the high background noise and reverberation effects in the closed test-section of their existing '40 ft x 80 ft' tunnel.

6. Concluding Remarks

Encouragingly successful noise experiments in subsonic windtunnels, particularly in those incorporating some acoustic treatment, have already included basic research studies on single and coaxial jets, jet interaction with airframe surfaces, airframe shielding of engine noise, sound refraction by wing vortex flows, airframe self-noise, engine-fan and helicopter-rotor noise. This is not to dispute that, as in the past with aerodynamic and aeroelastic testing, difficulties of model-simulation, of experimental measurement, and of analytical interpretation of results will continue to arise with aeroacoustic testing. For example, there have been apparent disagreements and lack of understanding because some forward-speed effects from flight tests on engine exhaust noise and from spinning-rig tests on exhaust-nozzle models with internal combustion systems exhibited a noticeable increase in noise over the forward arc, rather than the reduction expected from tunnel tests on simple pure jets. These past discrepancies can now be explained in terms of specific limitations arising from the particular testing methods, installation arrangements, analytical treatments and theoretical interpretation which could then be provided to take practical account of complex sources, interactions and propagation effects. Indeed, the critical comments made throughout this paper should be taken to signify realism not pessimism, already implying the attainment of more profitable and more precise techniques, and indicating even greater potential for application than would have seemed possible a few years ago.

As regards new tunnels for aeroacoustic testing of aircraft models (airframe + propulsors), the largest possible atmospheric design would be preferred with facility for providing a quiet open-jet test-section surrounded by an anechoic working-chamber, rather than a smaller pressurised version and a restrictive closed test-section. Such a tunnel should incorporate a good contraction-ratio ($\approx$ 10:1) as well as a quiet drive-fan, with some acoustic treatment in the low-airspeed regions both upstream and downstream of the test-section, commensurate with tolerable penalties in aerodynamic performance and cost.

Recent promising developments in directional acoustic receivers and other discrimination/correlation techniques should now be exploited, in part for model noise source diagnosis, but also to expedite extraction of the true source signal from any residual background-noise and reverberation in the working-chamber, and from any parasitic noise due to rigs or instrumentation inside the airstream. While these diagnostic and discrimination techniques tend to introduce much greater complexity of measurement and analysis, they could ultimately prove sufficiently practical and flexible to justify also worthwhile relaxation of tunnel acoustic treatment needs. For special cases at least, restrictions on aeroacoustic testing in modern aerodynamic tunnels could well be alleviated, allowing otherwise objectionable levels of background noise or semi-reverberant test-sections (closed as well as open), while taking advantage of the tunnels' large size, outstanding flow qualities (eg $u'/U < 0.2\%$), and higher maximum speeds ($U \geq 100$ m/s).

Following on the rapid developments in various acoustic tunnels and the further advances now feasible in measurement and analysis techniques, the provision of noise-models with better selective simulation of propulsor noise sources (in flight) and of propulsor/airframe airflow characteristics is next of vital importance. Here the term model is intended in its broadest sense of both practical design methods and theoretical frameworks, for the meaningful isolation and reliable representation of particular noise aspects, and for the complementary interpretation of results for small-scale and full-scale test conditions from ground-based facilities and flight. This task presents problems perhaps at least comparable with complex developments in aeroelastic models over 30 years ago or in powered-lift aerodynamic models over 20 years ago.

References

1. F.W. Armstrong & J. Williams: Some UK-Government Establishment research towards quieter aircraft. J.S. & Vib., Vol 47, No.2, pp.207-236 (1976).
2. J. Williams, et alia: Aerodynamic noise. AGARD LS-80 (March 1977).
3. T.A. Holbeche & J. Williams: Acoustic considerations for noise experiments at model-scale in subsonic windtunnels. RAE Tech Rep 72155 (July 1972).
4. J.E. Ffowcs Williams, et alia: Noise mechanisms. AGARD CP 131 (March 1974).
5. W.F. Brownell: An anechoic test facility design for the Naval Ship Research and Development Center, Carderock (USA). NSRDC Rep 2924 (Sept 1968).
6. W. Foley & R.W. Paterson: Development of the United Technologies Research Center acoustic research tunnel and associated test techniques. AGARD CP-174, Paper 7 (June 1975).
7. D.H. Hickey & M.W. Kelly: Aspects of a large-scale, subsonic, windtunnel design for propulsion noise research. AIAA Paper 73-1279 (Nov 1973).
8. R.K. Amiet: Correction of open-jet windtunnel measurements for shear layer refraction. AIAA Paper 75-532 (March 1975).
9. L.L. Beranek & T.J. Schultz: Noise and vibration control. McGraw Hill (1971).
10. K. Taylor: A transformation of the acoustic equations with implications for windtunnel and low-speed flight tests. RAE Tech Rep 77109 (July 1977).

NOTE - A more comprehensive list of about 130 references on windtunnels and other ground-based facilities with forward-speed representation for aircraft noise research is included in Paper 11 of AGARD LS-80 (March 1977).

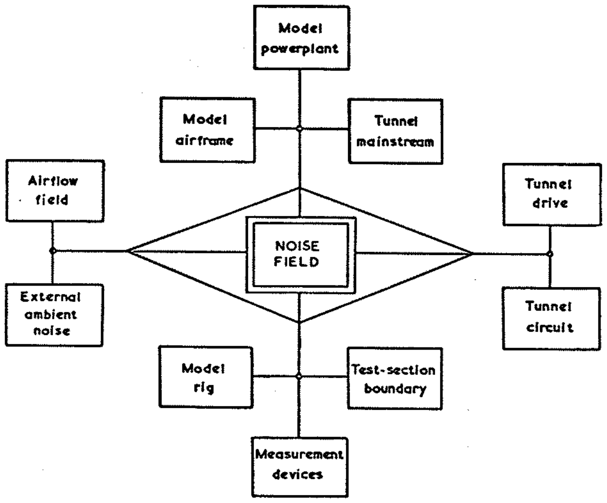


Fig 1 Simplified interaction element diagram

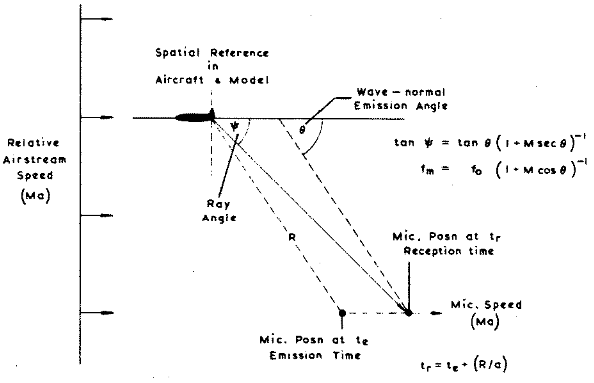


Fig 2 Ideal flight/tunnel equivalence

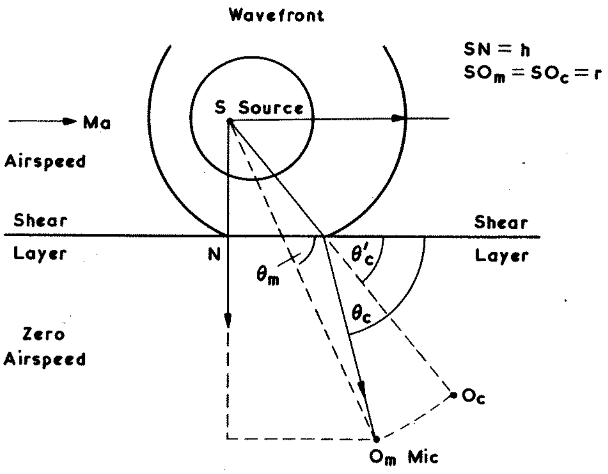


Fig 3 Tunnel shear-layer refraction principle

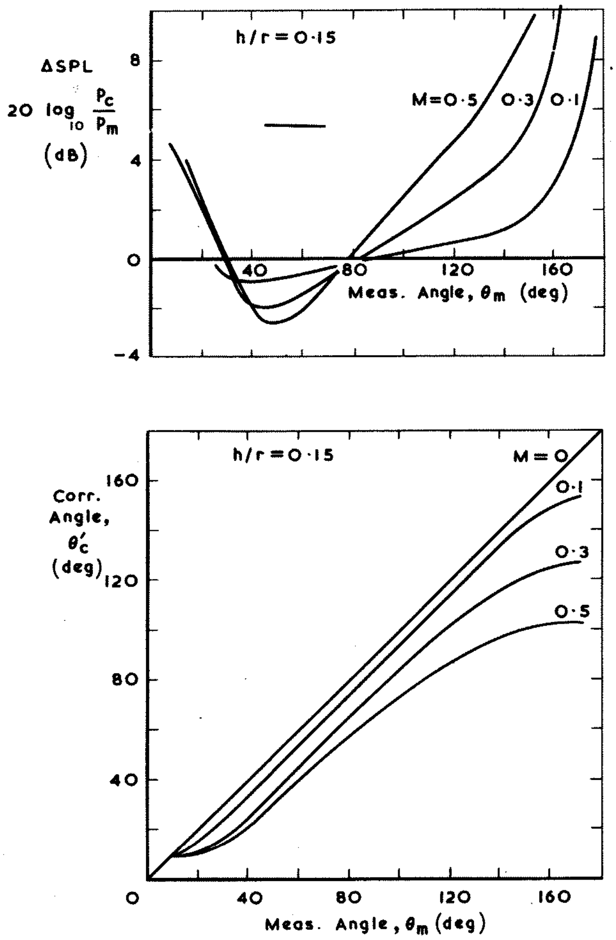


Fig 4 Tunnel shear-layer refraction corrections

For minimum frequency f_{min}

Far-Field in Airstream

$R_{air} > R_{far} = k_{far} \times (a/f_{min})$

eg $R_{air} > 1{\cdot}5 \times \frac{340\,m/s}{200\,Hz}$

$\approx 2{\cdot}5m$

Free-Field at Microphone

$B_{mic} > k_{mic} \times (a/f_{min})$

eg $B_{mic} > 0{\cdot}3 \times \frac{340\,m/s}{200\,Hz}$

$\approx 0{\cdot}5m$

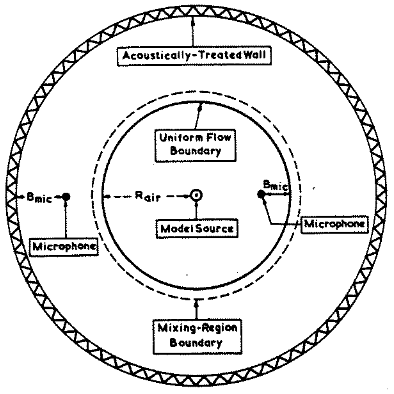


Fig 5 Acoustic constraints on tunnel size

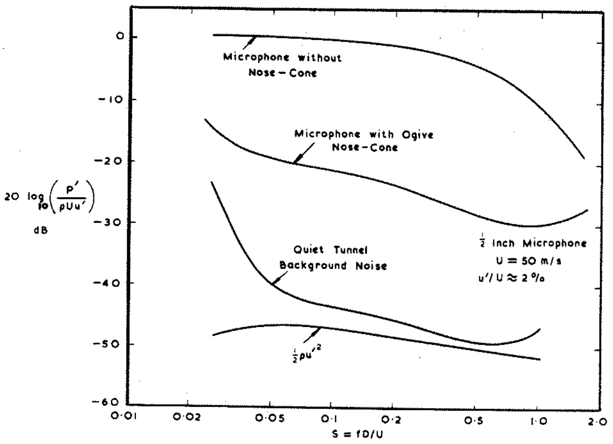


Fig 6 Comparison of microphone output and equivalent turbulence

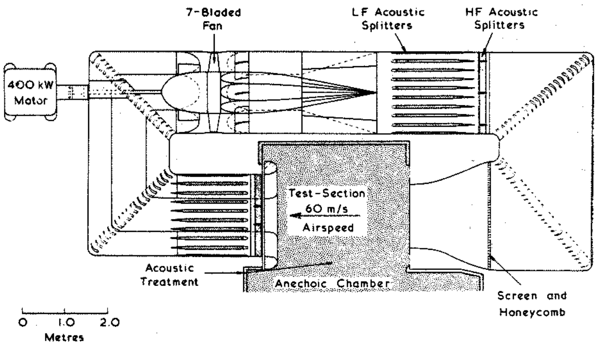


Fig 9 RAE 1.5m acoustic tunnel

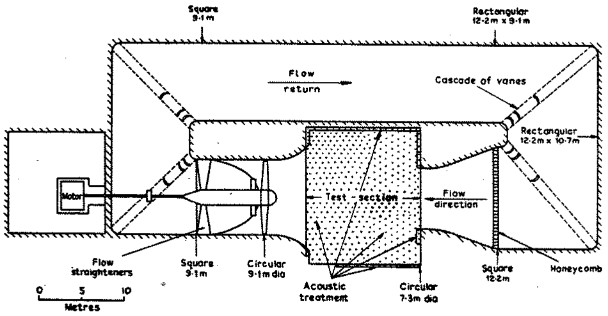
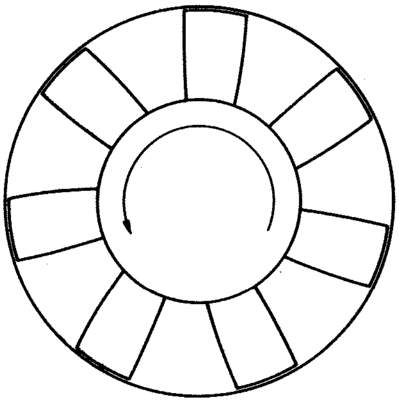


Fig 7 RAE 24ft anechoic tunnel



Fan diameter = 1.85 m Centrebody diameter = 0.97m
7 blades, chord = 0.37m

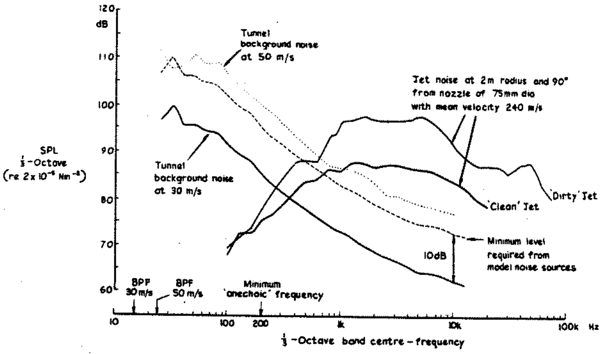


Fig 8 RAE 24ft tunnel background noise spectra and jet-model noise comparison

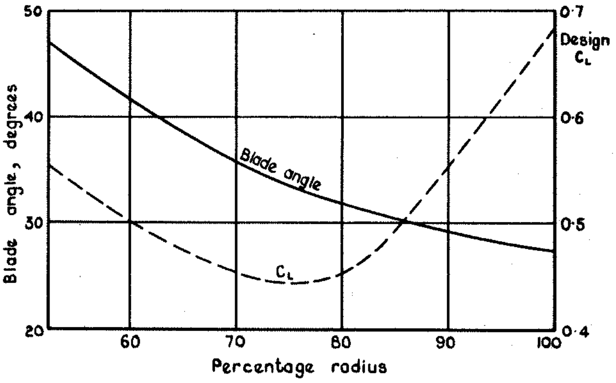


Fig 10 Fan design for RAE 1.5m acoustic tunnel

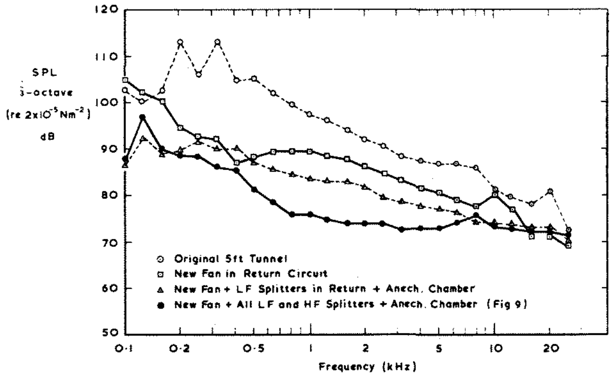


Fig 11 RAE 1.5m acoustic tunnel: noise characteristics at 50 m/s

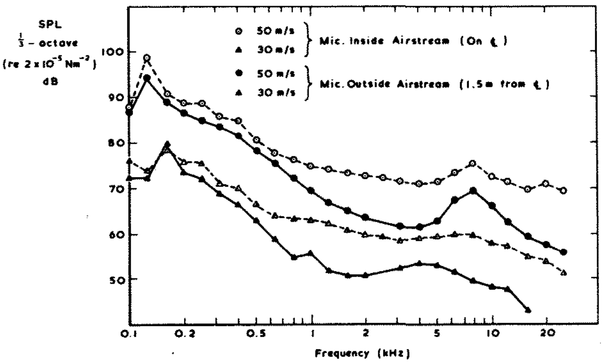


Fig 12 RAE 1.5m acoustic tunnel: variation of background noise with speed and measurement position

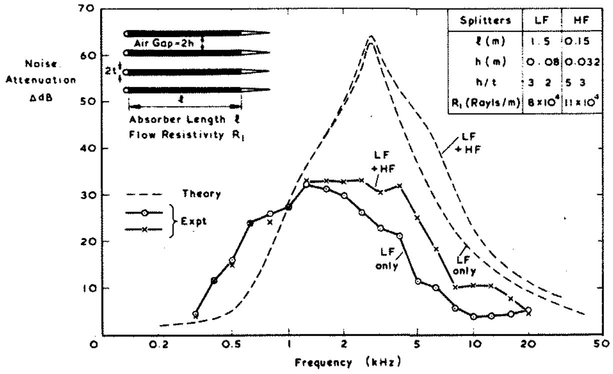


Fig 13 Efficiency of acoustic splitters at zero airspeed

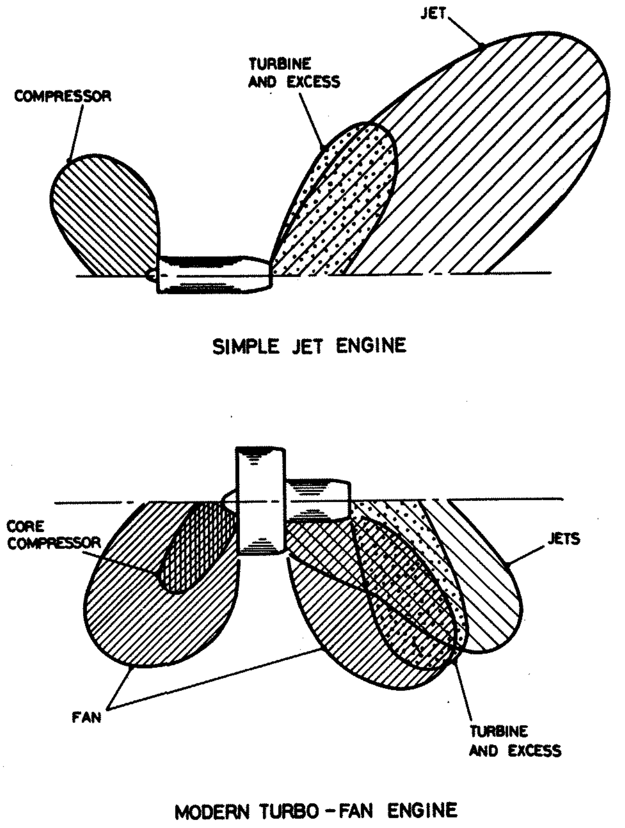


Fig 14 Engine noise components