RECENT DEVELOPMENTS IN NOISE RESEARCH AT NGTE

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Abstract

The evolution of research at NGTE on the aircraft noise problem, from its beginnings in the 1950's, is first outlined briefly. The further expansion of NGTE powerplant noise work which began in the late 1960's is then dealt with in greater detail.

Experimental facilities are described and some results are given of recent studies of jet and associated exhaust system noise, fan noise, and the performance of absorbent liners for powerplant ducting.

The planning, building and bringing into operation of a major Noise Test Facility for use largely on behalf of industry is also described.

I. Introduction

The noise nuisance caused to communities around airports is one of the greatest problems besetting present-day civil aviation. Considerable effort is being expended to meet the challenge of lessening the nuisance without impairing the continued development of air transport. Governments, operators, manufacturers and research institutions are all playing a part. In addition to local regulations designed to control noise near specific airports, legislation based on international agreements has for some years required new types of subsonic jet airliner to be certificated as meeting given noise levels. Currently, the successful development of 'hushkits' is enabling many older types to be brought within these levels. At the same time, it appears likely that still more stringent limits will be set for new types as the future unfolds.

Against this background, low noise is now a major design objective for new civil aircraft. But to retain competitive economics it is essential that any resultant penalties in performance, weight or cost be kept to a minimum - indeed, herein lies the essence of the technical challenge. Work related to the noise problem therefore forms a significant part of current aeronautical research and development activity in the major aircraft manufacturing countries. In the UK, a comprehensive programme is in progress, covering relevant aspects of aircraft design and operation as well as the noise problems of the powerplant itself. Most of the research is government funded, while government and industry share the cost of certain engine 'demonstrator' exercises and flight trials. The overall programme involves the industry, government establishments and several universities, and is carefully coordinated with the object of gaining maximum effect from the available resources. The National Gas Turbine Establishment plays a significant part on the powerplant side, both in the very important coordinating role and as a research and test centre in its own right. While this paper is largely concerned with the latter aspect, it is hoped that some impression of the wider perspective will also be conveyed.

II. The National Gas Turbine Establishment and its role

The National Gas Turbine Establishment is the UK government centre for research and development on gas turbines and jet propulsion. It arose from origins in government research and industry. In the early days, work on aeronautical applications of the gas turbine was pursued by a team in the Engine Department of the Royal Aircraft Establishment, as well as by Power Jets Ltd, the original UK jet engine company led by Whittle. The two were merged in 1944 when a nationalised company, Power Jets (Research and Development) Ltd was formed - the main body of which was reconstituted in 1946 as the National Gas Turbine Establishment under the then Ministry of Supply.

The Establishment acts as a research and test centre for gas turbine powerplants and jet propulsion. It is mainly, but by no means solely, concerned with aeronautical work; for instance, there is on site an important naval gas turbine test house. In addition to a wide range of equipment used for research, there are very large scale facilities devoted to the testing of aero-engines, under simulated flight conditions, on behalf of industry. Other functions of the Establishment are to provide technical advice on matters within its field to government departments, and to oversee (as well as participating in) the propulsion side of the UK government-sponsored aeronautical research programme. The latter task involves general coordination of the intramural and extramural parts of the programme, assessment of contractor research proposals on an item by item basis, and monitoring of these items as the research work proceeds. Consequently, members of the various NGTE research departments maintain close contact with their counterparts in industry, universities and other government establishments.

Although the Establishment is incorporated in the Ministry of Defence (Procurement Executive), it also has close links with the Department of Industry, arising from the latter's responsibility for civil aerospace policy and funding.

III. The evolution of noise work at NGTE

Studies at NGTE of the jet engine noise problem began in the 1950's. The realisation was then growing that the future expansion of air transport, coupled with the widespread use of the jet engine in civil aircraft, could produce a serious social problem. At that time, and extending into the early 1960's, jet engine noise was predominantly due to the propulsive jet itself as it mixed with the atmosphere. It was already clear, though, that noise emanating from the blading inside the engine would become more significant in the future, and Lloyd, in his 1959 paper(1), showed Hargest's tentative correlation of compressor noise on a basis used previously for ventilating fans. As engine design evolved, to fulfil the promise of improved fuel economy offered by the ducted fan cycle, turbomachinery noise did indeed increase in importance, and showed itself to have a high nuisance value, due to its tonal properties. From the early 1960's on, its various aspects have been studied intensively at many firms and research institutions on both sides of the Atlantic, including NGTE(2,3,4).

Always important in studies of nuisance caused by noise, is the question of how to make quantitative comparisons between sounds of differing frequency content. This problem has required much attention in the aircraft noise context. The Establishment played a significant part by mounting, between 1959 and 1969, a series of psycho-acoustic experiments(5,6,7,8) involving many thousands of subjects and covering many aspects of fixed-wing aircraft and helicopter rotor noise. This provided scientific consolidation for the PNdB and EPNdB scales, the latter subsequently being adopted as a basis for internationally agreed legislation.

The 1960's also saw the commissioning at NGTE of an anechoic chamber (described later) for model-scale work on jets, and studies(9) of jet noise on a research basis and in direct support of projects. Full-scale flight work included an investigation of helicopter noise(10), and preliminary studies of the effects of wing vortex refraction(11), and shielding, in modifying the propagation of engine noise.

In the late 1960's a further expansion of powerplant noise work at NGTE was put in hand, and the developments stemming from that time form the main subject of this paper. These developments can be considered under two separate, though related, headings:-

(a) An expansion of the research, with new facilities being introduced for work on fan noise and acoustic absorbers.

(b) The planning and building of a major Noise Test Facility, to be used largely for work on behalf of industry. This comprises two units - the Absorber Facility, for testing absorbent panels under conditions approximating to those found in powerplant ducting, and the Anechoic Facility, for tests on engine and large-scale model exhaust systems.

The following sections deal in turn with selected aspects illustrating these developments.

IV. Jet noise research

Although the jet formed the dominant noise source of the simple turbojet engine, and therefore attracted the attention of research workers at an early stage, jet noise continues to provide much scope for study. Items of interest include the very high velocity jets of supersonic airliners, the low velocity co-axial jet systems of high-bypass engines, the question of how jet noise varies between static and flight conditions, and the problem of improving the effectiveness of 'silencer' devices. NGTE has been active on all these topics, with contributions ranging from experiments aimed at obtaining good-quality basic data for general use, to tests on exhaust system designs for the Concorde. Some of the more basic work is now outlined.

Jet noise - static conditions

A necessary first step towards the understanding of jet noise from aircraft in flight is to study the simpler situation where the jet nozzle is stationary relative to the surrounding atmosphere. The anechoic chamber facility used at NGTE for such work is shown diagrammatically in Figure 1. This was constructed in 1965/66, and has since been operated for thousands of hours on a variety of programmes.

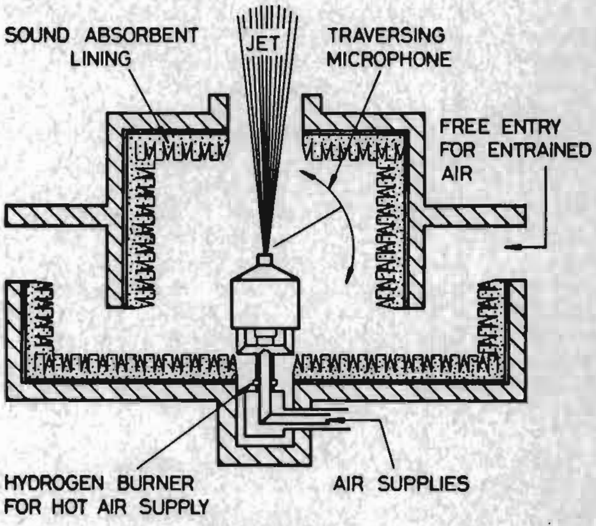


FIG. 1 JET NOISE CHAMBER

The chamber is 5.2 m square, with an internal height of 4.6 m, and is effectively anechoic at frequencies above about 250 Hz. Exhausting the jet through an aperture in the roof, while entrained air enters around the sides, keeps the chamber at ambient conditions even when the jet is run continuously at high temperature. Air for the jet is supplied at a maximum pressure of 3.5 bars, and heating is by means of a hydrogen burner situated below the jet rig.

The noise measurements are taken by a polar-traversing microphone. The nearby control room is equipped with systems allowing complete remote control, with television surveillance of the chamber. The control room - which also serves the fan noise research chamber, described later - is provided with data acquisition and analysis equipment capable of handling signals at frequencies up to 100 kHz.

In recent years an important objective has been to obtain improved basic data on the noise of single and co-axial jets in the low-to-medium velocity range. This régime is not without its experimental problems, for the jet noise can become so low that extraneous upstream noise sources, such as control valves, can intrude upon, and even dominate, the measured results. Careful rig design and development therefore becomes essential.

Work by Cocking aimed at covering both single and co-axial jets began in 1971, following a series of experiments(12) on single cold jets in the NGTE chamber by Ahuja of Rolls-Royce. Both workers employed a plenum-type silencer between the compressed air supply system and the test nozzle, with the objects of suppressing rig noise and ensuring an aerodynamically 'clean' jet. Cocking's silencer was designed to deal with two air streams for co-axial jet studies, with a hot primary flow. However, his work was initially concentrated on exploring the noise characteristics of the primary jet alone over a range of temperature and velocity, and this study in itself produced results which generated widespread interest.

Although at the higher jet velocities the noise of the jet was found to reduce with increasing temperature at a given velocity, a 'cross-over' effect was observed at about 250 m/s - below which the noise increased with temperature. This result was unexpected, prompting careful checks aimed at establishing the validity of the measured data - including substitution of an electric heater for the hydrogen burner system. Such activities produced no significant modification of the results, and shortly afterwards it emerged in the course of Concorde collaboration that a similar trend had been discerned in France. The results were found to be complementary, and have been summarised in a joint SNECMA/NGTE paper(13). The NGTE work is described more fully in Reference 14. Further confirmation of these temperature effects has now been obtained elsewhere, although the theoretical implications are still under debate.

The NGTE work has since been extended, as planned, to measure the noise characteristics of co-axial jets. Table I, below, shows the wide range of geometric and operating parameters covered. For all cases, the primary nozzle diameter was 4.5 cm and the secondary jet temperature was 290°K.

PRIMARY JET VELOCITY	V_{PRIM}	200, 245, 305, 380 m/s
SECONDARY / PRIMARY JET VELOCITY RATIO	$\frac{V_{SEC}}{V_{PRIM}}$	0, 0·2, 0·4, 0·6, 0·8, 1·0
SECONDARY / PRIMARY NOZZLE AREA RATIO	$\frac{A_{SEC}}{A_{PRIM}}$	2:1, 4:1, 6:1
NOZZLE AXIAL POSITIONS		COPLANAR AND PRIMARY EXTENDED BY 3 PRIMARY NOZZLE DIAMETERS
PRIMARY JET TEMPERATURE	T_{PRIM}	300, 700, 900 °K

TABLE I CO-AXIAL JET NOISE TEST RANGE

Space limitations clearly preclude more than a brief indication of the results, but Figure 2 illustrates some important effects in showing how the total sound power of a co-axial jet system varies with the ratio of secondary to primary jet velocity. As the secondary jet velocity is increased from zero, the total noise falls initially, due presumably to the effect of the secondary jet in reducing the intensity of mixing in the primary jet shear layer. However, the noise which arises from mixing of the secondary jet with the atmosphere increases progressively, with the result that the total sound output of the system reaches a minimum and then rises again, exceeding that of the primary jet alone at velocity ratios greater than about 0.7.

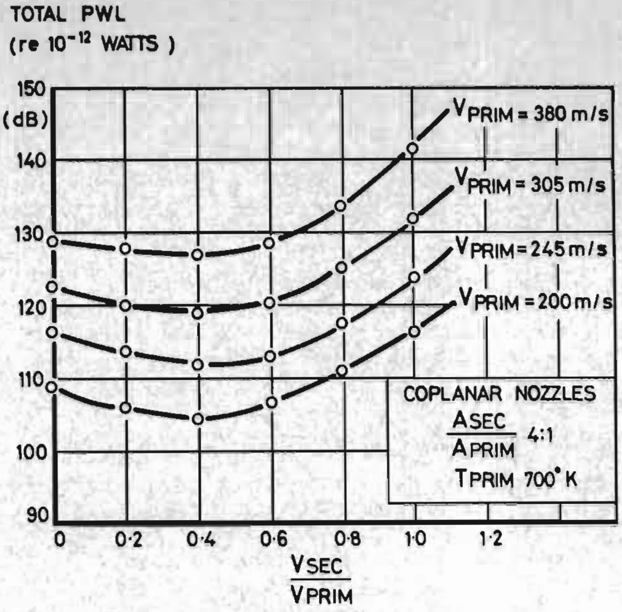


FIG.2 EFFECT OF VELOCITY RATIO ON PWL

The trends shown in Figure 2 are typical of the results obtained over the whole range of tests. The most significant parameters were found to be primary jet velocity, secondary/primary velocity ratio, and, to a lesser extent, nozzle area ratio. The effects of primary temperature and nozzle axial positioning appeared to be small. The full results of the study, which are given in Reference 15, have been used to formulate a revised prediction method for co-axial jet noise.

Jet noise with flight simulation

The experimental problems of studying jet noise under forward speed conditions are much more difficult than those associated with static testing. Some kind of flight simulation with closely controlled conditions is desirable, because tests using actual aircraft tend to be both expensive and technically unsatisfactory. In addition to the often complex make-up of the engine noise itself, the aircraft can modify its propagation by such mechanisms as shielding, reflection and refraction through vortices. Furthermore, uncertainties comparable with the changes under study may arise in correcting flight data to standardised atmospheric conditions. Efforts have therefore been made in recent years to develop techniques for model-scale research by using a true moving jet nozzle source or by surrounding the jet by a flow of air.

The NGTE approach to this problem has been influenced by the availability at the nearby Royal Aircraft Establishment of a large wind-tunnel which has been modified for acoustics work. This is the well-known 24 ft (7.3 m) diameter tunnel, built in the 1930's. It has an open-jet working section situated within a large chamber recently equipped with sound-absorbent treatment. Noise studies of model jets using this tunnel began in 1973, with the collaboration of RAE workers.

Figure 3 is a wide-angle photograph showing a model jet rig mounted in the working section. On the right-hand side is seen the downstream flow collector, within which is the tunnel driving fan.

The proximity of this fan, coupled with the return-circuit nature of the tunnel, were significant factors in the decision to restrict the work so far to cold jets. Also visible in the photograph is the traversing microphone, mounted within the tunnel flow. The test jet is 10.2 cm diameter.

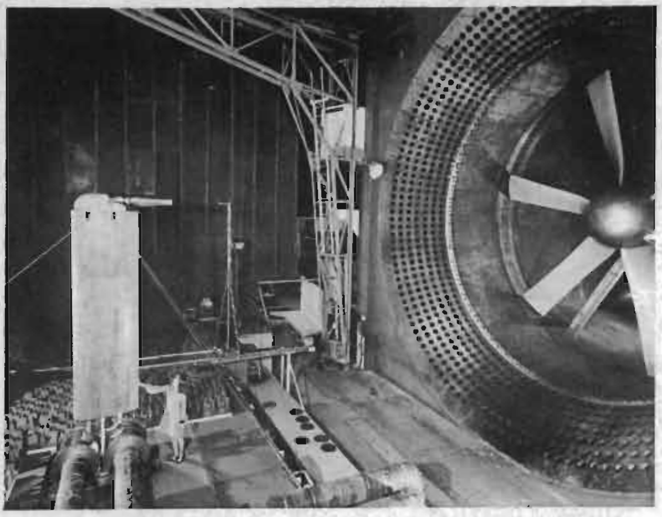


FIG. 3 JET MODEL IN R.A.E. 24 FT. WIND TUNNEL

Although the tunnel (described more fully in Reference 16) is capable of working section flow velocities up to about 50 m/s, most of the work with jets has been done at velocities of 30 m/s or less to ensure an adequate margin between the noise of the jet and the tunnel background noise. Figure 4 presents a comparison of noise spectra showing that, except at the low frequencies, tunnel noise at 30 m/s does not interfere with jet noise measurements.

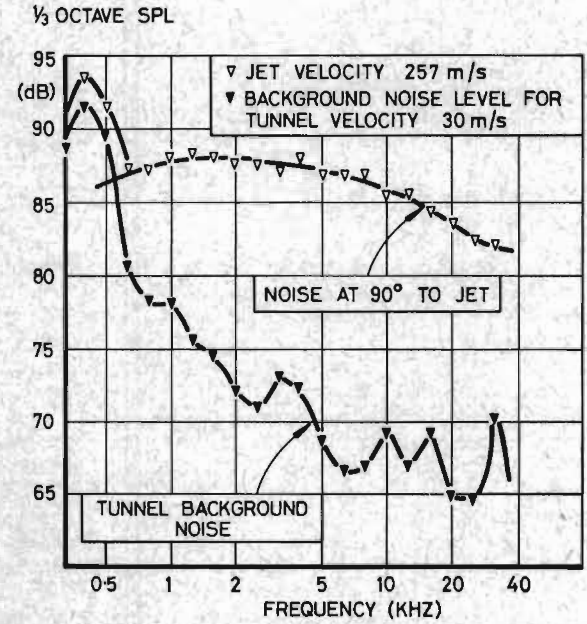


FIG. 4 JET AND BACKGROUND SPECTRA

Figure 5 shows the measured spectra at 35° to the jet axis for various tunnel speeds. These spectra incorporate the Doppler frequency correction needed to render the tunnel measurements (where there is no relative motion between jet nozzle and microphone) analogous to the case where an aircraft is flying past a fixed observation point. It is clear that, although the total range of tunnel speed is not large, the small differences in noise level are clearly distinguishable. This consistency in the measured results, which forms one of the most encouraging features of the jet work done so far in the RAE tunnel, is further emphasised by Figure 6. This shows the reduction in overall sound pressure level at 35° to the jet axis with jet/tunnel relative velocity for a larger number of test results. Although test velocity limitations were such that the OASPL changes were restricted to 4 dB or less, the consistency of the data allows a mean line to be drawn with some confidence. On Figure 6, V_j is jet velocity, V_T is tunnel velocity and V_{TO} is the velocity induced by the jet in the tunnel working section under nominally 'static' conditions when the tunnel is not being driven by its fan.

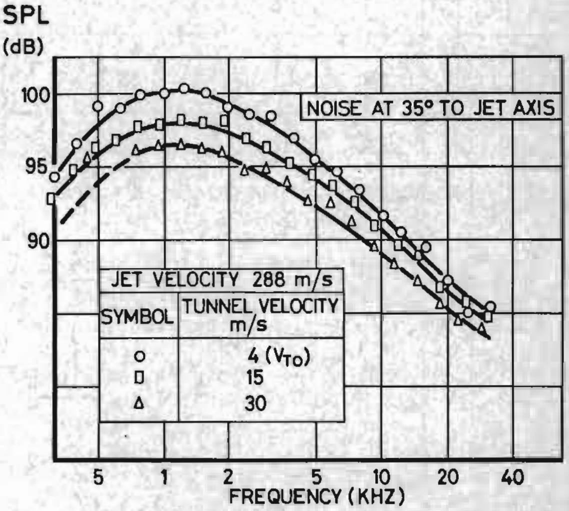


FIG.5 MEASURED SPECTRA AT VARIOUS TUNNEL VELOCITIES

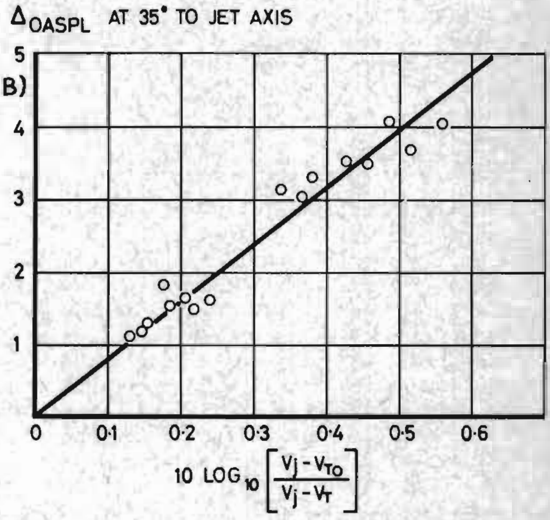


FIG. 6 REDUCTION IN OASPL WITH TUNNEL FLOW

The results of this study of the effect of 'flight' on a cold subsonic jet are given fully in Reference 17, and are summarised in Table II. The OASPL data can be correlated in terms of the equation shown, with indices 'n' and 'm' being deduced from the measurements under static and forward speed conditions. While jet noise is reduced by forward speed at all angles tested, the reduction is less at high angles to the axis. It is interesting that this observation differs somewhat from results obtained by NASA(18) which, in the terms of the correlation used here, appear to imply a value for 'm' of 6 at both 20° and 90° to the jet axis. While the NASA work covered a much larger range of 'flight' velocity, the flight simulation was provided by an airflow of much smaller size in relation to the test jet than that given by the RAE tunnel. Another difference was that, in the NASA work, the microphone was mounted outside the flight simulation flow.

$$OASPL_\theta \propto V_j^{\,n}\,(V_j - V_a)^m$$

ANGLE TO JET AXIS	n	m	n + m STATIC EXPERIMENT
35°	1·8	8	9·8
60°	2·2	6·4	8·6
90°	3·1	5·1	8·2
120°	2·9	5·1	8·0

TABLE II DEPENDENCE OF OASPL ON JET AND TUNNEL VELOCITIES

More important than the detailed differences between the NASA and NGTE results is the fact that both studies showed basic jet noise reducing with forward speed at all angles tested. In contrast, actual jet engines often show virtually no exhaust noise reduction with flight, at angles around 90°. This difference is considered to be due to the presence in engines of 'excess' noise sources which form another important focus for research - see next section.

It is planned to continue the development of jet testing techniques using the 24 ft tunnel. Some preliminary work has recently been done with cold co-axial jets, although the range of conditions so far covered is small. Consideration is also being given to the possibility of making tests in the tunnel with heated jets.

V. Excess or tailpipe noise research

It has been clear for some years that the noise of a typical engine exhaust cannot be fully accounted for in terms of basic jet and turbine noise. The additional component, which is particularly evident at reduced-power conditions, has been variously described as excess noise, internal noise, core noise, tailpipe noise, etc - the variety of terms reflecting the lack of understanding of its origins and characteristics. Research aimed at clarifying this situation, and hence indicating ways by which noise reductions may be achieved, is proceeding on both sides of the Atlantic and commands significant effort at NGTE.

One of the approaches followed at the Establishment has been to study the noise characteristics of a model exhaust system. The model, having a jet-pipe diameter of 13 cm and a convergent nozzle, was an accurate representation of an engine exhaust system downstream of the turbine exit plane. It therefore included the turbine exhaust cone and the cambered struts which are designed to remove swirl from the turbine exit flow in the engine. Upstream of the turbine exit plane the model departed from the engine configuration and simply consisted of a converging annular approach passage fitted with 12 adjustable vanes which could be set to produce varying amounts of swirl in the flow. The model was run with unheated airflow in the NGTE jet chamber (Figure 1).

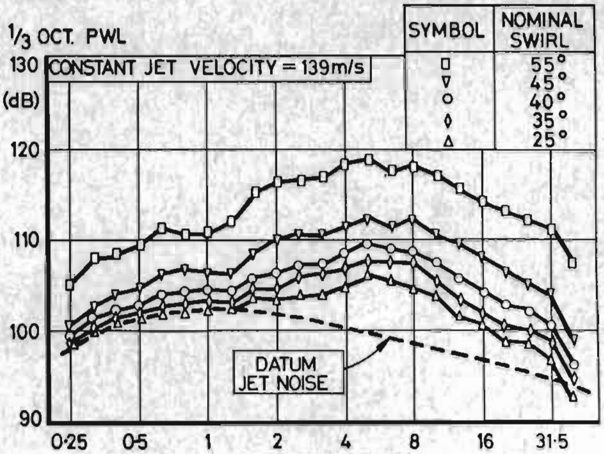


FIG.7 EFFECT OF STRUT ENTRY SWIRL ON EXHAUST NOISE

Figure 7 shows the sound power spectra at a constant jet velocity but with varying swirl at entry to the turbine exhaust struts. It is clear that the effect of swirl is strong, the spectra rising progressively as swirl is increased. The 'datum' jet noise shown as a broken curve was obtained from a previous series of tests on the same model with the whole centre-body and strut system removed. It appears that the measured spectra change somewhat in character at about 1.2 kHz, above which frequency they display distinct 'humps' even at the lower swirl angles tested. It is suspected that these two regions distinguished in the spectra may represent different noise sources. Further discussion here is concentrated on the higher frequency parts of the spectra, which exhibit both the highest noise levels and the greatest increases above the basic jet noise.

By taking the peak of each measured spectrum, and subtracting from it the jet noise level at the same frequency, a maximum 'excess' or 'internal' noise component can be deduced for each of the many test cases. Figure 8 shows the correlation of this noise component, both in terms of level and frequency, against turbine exhaust strut incident velocity for a constant swirl angle. It is seen that the large number of data points fall closely about a $(\text{velocity})^6$ line for power level, with peak frequency directly proportional to velocity (ie constant Strouhal number). Although similar correlations for lower angles of swirl indicated a dependence of power level on $(\text{velocity})^6$ throughout, the peak frequency dependence fell to $(\text{velocity})^{\frac{1}{2}}$ at swirl angles of 45° and below.

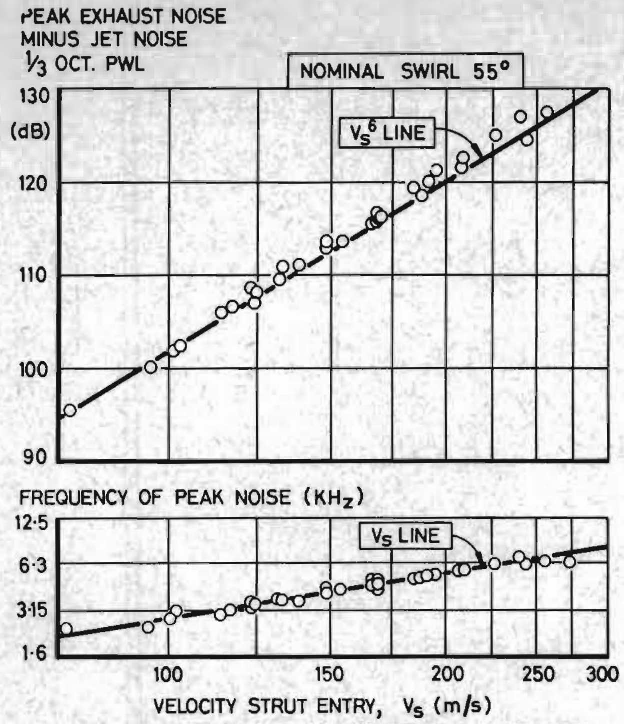


FIG. 8 CORRELATION OF INTERNAL NOISE FOR ENTRY SWIRL 55°

Finally, a correlation in terms of swirl angle is shown in Figure 9, where the effect of incident velocity has been allowed for on a $(\text{velocity})^6$ basis. The curve of internal noise versus swirl has a distinct minimum at a mid-annulus swirl angle close to the aerodynamic design setting of the struts, showing that the noise increases as the angle of incidence moves away from the design value in either direction.

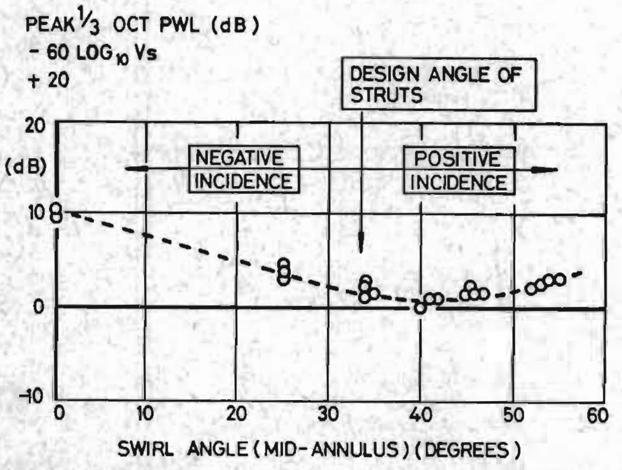


FIG.9 VARIATION OF INTERNAL NOISE WITH SWIRL

This example(19) of a typical investigation illustrates the value of model experiments in enabling selected effects to be isolated and studied in a controlled manner. The large and independent variations of swirl and velocity achieved in this study could not have been obtained using an actual engine, where the two parameters are closely linked and vary over a relatively narrow field during engine operation.

On the other hand, the results of model work need to be kept in perspective. Although it is considered that the study described has clearly revealed the existence of at least one strut-based noise source on the model, this by no means proves that noise from the turbine exit struts is a highly significant source on engines. If progress is to be made in unravelling the engine excess noise problem, it is essential that model studies such as this should be accompanied by careful diagnostic work on engines. Present indications are that although strut noise may be significant in some engines at low-power conditions, this type of source does not account for all of the observed effects. Investigation of the various possibilities continues, involving analysis of engine data and further model tests. One general impression which has emerged is that turbulence in the flow crossing the nozzle plane may be a significant factor in the production of excess noise both under static and flight conditions over a wide range of jet velocity.

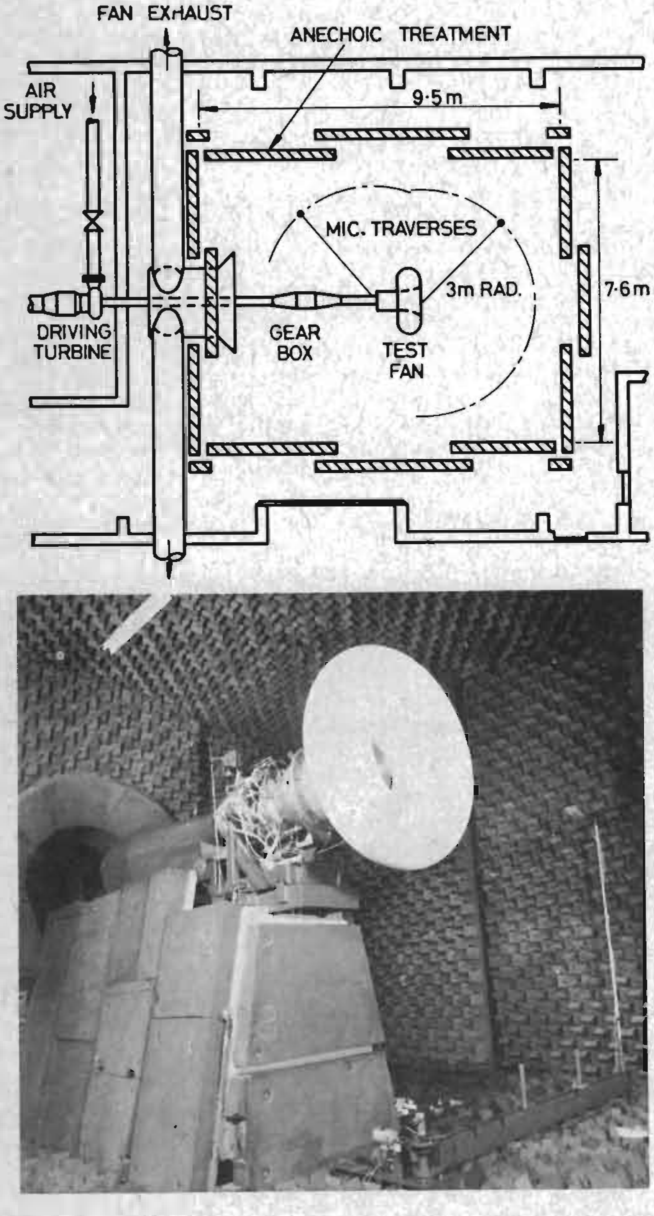
VI. Fan noise research

Studies of compressor noise at NGTE began in the late 1950's, with preliminary work(1) on the correlation of noise from various machines. During the 1960's a number of experimental investigations(eg 2,3) were pursued, using microphones mounted in the approach duct to the compressor. Although appropriate for certain types of work, this 'in-duct' measurement technique is somewhat limiting in that it precludes observation of the far-field directivity characteristics - a matter of significance both in aircraft noise prediction and in research on detailed noise generation and propagation phenomena. It was therefore decided in the late 1960's that an anechoic chamber suitable for compressor noise research would be built at the Establishment. This was envisaged as complementing the large facility at Ansty(20) which had been put into operation in 1967 as a joint enterprise between government and the engine industry.

The NGTE facility was constructed inside an existing building, and began its commissioning trials in late 1971. It differs from the Ansty facility in a number of respects, notably in being appreciably smaller and in the positioning of the compressor test rig in the chamber. At Ansty the machine on test is mounted in a wall, so that only the intake, say, is actually within the chamber. When rearward noise measurements are required it is necessary to reverse the installation. In contrast, the test machine is placed centrally in the NGTE chamber, allowing observation of the whole noise field without changing the installation. This feature makes the facility particularly suitable for studies of configurations where changes to the intake might affect the rearward, as well as the forward, noise - for example, high Mach number intakes.

The facility is illustrated by the schematic plan view of Figure 10 and the photograph, Figure 11. The chamber consists of panels mounted in a framework of standard scaffolding which is secured to the roof beams of the building. The panels are of 15 cm square mesh with polyurethane foam wedges inserted in the mesh spaces. The wall panels are offset to admit induced air to the chamber. Exhaust air is collected by a large duct surrounding the drive system, whence it is discharged from the building. The 30 cm long wedges render the chamber effectively anechoic at frequencies above about 400 Hz. Polar microphone traverses at 3 m radius can be performed simultaneously in the forward and rearward arcs.

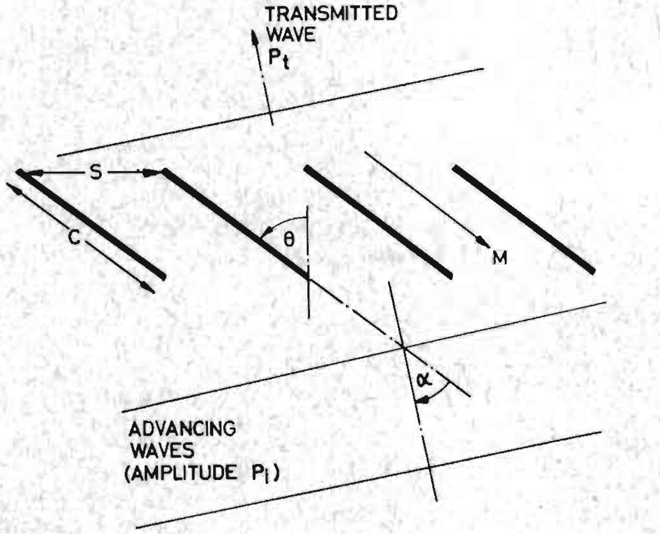
The test machine is powered by a turbine which is itself driven by air from a site compressor. The power available, about 1000 kW, is sufficient to allow testing of model single-stage transonic fans of up to 40 cm diameter. Indeed, it was an important design requirement for the facility that it should be capable of testing a range of such fans which are in use for both aerodynamics and noise research at Rolls-Royce as part of the UK government-sponsored propulsion research programme.



FIGS. 10 & 11 N.G.T.E. FAN NOISE FACILITY

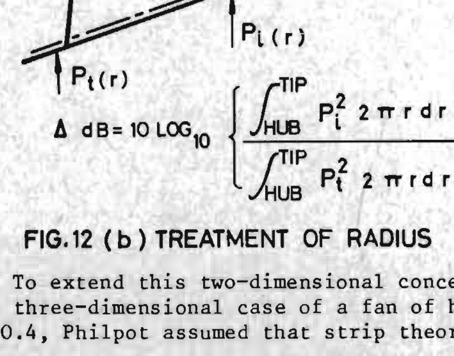
A study which took advantage of the forward and rearward noise measuring capability of the rig was made recently by Philpot$^{(4)}$ using one of the transonic research fans referred to above. He applied the theory of sound propagation through a blade row as developed by Amiet$^{(21)}$, to estimate the 'blockage' effect of the rotor on tone noise arising from rotor/stator interaction and propagating forward against the airflow. This estimate was then compared with the measured difference between rearward and forward arc tone levels.

The essentials of Amiet's theory are illustrated in Figure 12(a). The rotor blades are idealised as a two-dimensional cascade of flat plates with a flow of constant Mach number through them. Plane sound waves approach from the downstream direction and an energy split occurs at the 'rotor' trailing edges, part of the sound passing on through the cascade and the rest being reflected back. The amount transmitted forward depends on the cascade Mach number and the angle of the incident waves relative to the cascade. The theory is simplified by assuming that only plane wave propagation occurs in the cascade passages.



$$\frac{P_t}{P_i} = F(M, \alpha, \theta, S, C)$$

FIG.12 (a) ROTOR BLOCKAGE–TWO DIMENSIONAL THEORETICAL MODEL



$$\Delta\ \mathrm{dB} = 10 \log_{10} \left\{ \frac{\int_{\mathrm{HUB}}^{\mathrm{TIP}} P_i^2\, 2\pi r\, dr}{\int_{\mathrm{HUB}}^{\mathrm{TIP}} P_t^2\, 2\pi r\, dr} \right\}$$

FIG. 12 (b) TREATMENT OF RADIUS

To extend this two-dimensional concept to the highly three-dimensional case of a fan of hub/tip ratio 0.4, Philpot assumed that strip theory principles, familiar in aerodynamic analysis, could be used without undue loss of precision in this essentially acoustic problem. Sound propagation through the rotor was considered along five streamlines as shown in Figure 12(b) and the attenuation calculated at each one using the two-dimensional theory referred to above. The wave angles were derived using the tangential phase Mach numbers of the various circumferential duct modes which can be calculated for interaction tone noise at any fan speed. The net attenuation of the rotor blade row as a whole was then determined by summing the acoustic pressure distributions, upstream and downstream of the blades, from hub to tip. For this, the spanwise distribution of the incident acoustic pressure was assumed to follow the estimated unsteady force distribution on the stators, since the axial gap between rotor and stator rows in this machine was small.

Figure 13 shows a comparison of the estimated and measured differences between rearward and forward sound power level for the second harmonic tone (which is normally the most troublesome in engines). It is seen that theory and experiment are in quite good agreement over much of the fan speed range, though at tip speeds above about 300 m/s the theory underpredicts the attenuation by up to 5 dB. It is considered that, bearing in mind the simplifications and assumptions involved in the theory, the degree of correspondence found between these results is distinctly encouraging.

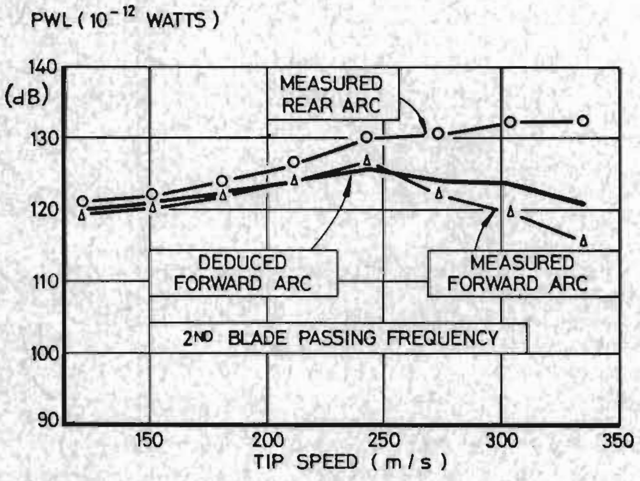


FIG 13 ROTOR BLOCKAGE - COMPARISON OF EXPERIMENT WITH THEORY

Some consideration has also been given to how rotor blockage might be maximised - the situation of main interest for an aircraft application being the approach-to-land condition, where forward noise from the engine has a considerable nuisance value. One approach would be to bias the design of fans so as to produce higher rotor Mach numbers, as rotor blockage is sensitive to blade relative Mach number. But such a move would have other, less desirable consequences, both for aerodynamic performance and noise generation, and can therefore be regarded as not beneficial overall. However, the rotor blockage effect is also increased by increasing the angle of incidence of the advancing waves to the rotor trailing edges, which may be achieved by altering the numbers of stator blades relative to the rotors, (thus altering the mode phase velocities). Figure 14 gives an indication of how the calculated blockage effect varies with the ratio of number of stators to number of rotor blades for the particular fan used as the subject for this study. The curve for 75% blade height corresponds to what might be expected for the noise generated in a 'bypass' section, and that at 25% for noise generated at the core engine stators. The geometries and flow Mach numbers are such that the bypass section attenuation is clearly the more favourable, but for both bypass and core engine sections the attenuation rises progressively with stator/rotor blade number ratio. For other transonic fans, a similar picture would be expected although the attenuation and its rate of change with stator/rotor blade number ratio would naturally differ from one design to another.

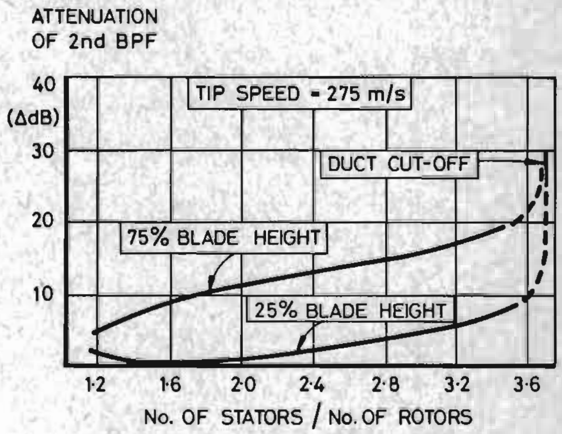


FIG.14 ROTOR BLOCKAGE - DEPENDENCE ON STATOR / ROTOR NUMBERS

The overall fan noise problem has of course many aspects and a change which may benefit one component may be unattractive from other points of view. Fan noise studies at NGTE are therefore broadly based and the work described above represents only one facet, presented here by way of illustration. The physical processes of noise generation are only partially understood and in order to make progress in this area we are, for example, making increasing use of hot wire techniques to study intake turbulence and the structure and distribution of the rotor wake flows - both of which play a significant part in noise generation. Other current projects include work on the correlation of broadband noise with fan design parameters, the noise characteristics of fans of more advanced duty than those in use today and the combination of absorbent liners with fans - the latter study being associated with work in the Absorber Facility to be described later.

VII. Research on acoustic absorption

An important result of the evolution of engine design from the simple turbo-jet to the high bypass ratio engines of today is that more of the major noise sources are now to be found within the powerplant envelope. The principle of acoustic absorption within the powerplant ducting can therefore be applied to reduce the total noise propagated from the aircraft. Although absorbent linings are already used in current powerplants, much scope remains for the further exploitation of this technique. Indeed, the degree of noise reduction achievable in future engines without incurring undue performance and weight penalties, will depend substantially on the rate of development of absorber technology.

NGTE is heavily committed to work in this field, particularly in connection with the large Absorber Facility of the Noise Test Facility, described later. Although very largely devoted to work on government-sponsored industry test programmes, that Facility is also used for NGTE in-house research. For example, a study now in progress involves comparison of the noise attenuation produced by given sets of duct liners mounted first in a fan intake, using the fan noise facility already described, and then in the large Absorber Facility. But absorption studies at NGTE began some time prior to the building of the latter, using small-scale rigs which are still employed for basic research and the development of measuring techniques.

The first absorbent duct rig at NGTE was established in the late 1960's, by the conversion of a set of old solid-fuel bunkers to produce simple but adequate reverberation chambers. A duct of square cross section was installed between these chambers and high levels of sound were obtained by using a Hartmann Generator noise source. This rig is shown schematically in Figure 15. Detachable panels in the duct walls permit experiments both with plain 'hard-wall' surfaces and with absorbent liners. In this simple rig there is no capability for passing a steady air flow through the duct to simulate the powerplant environment. However, another small duct rig which is otherwise similar in overall concept does incorporate this feature - as does the large Absorber Facility itself.

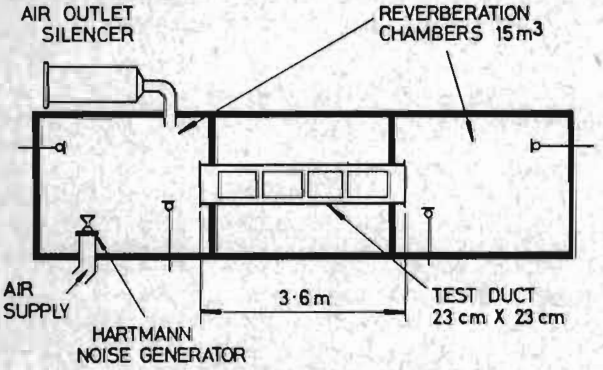


FIG.15 STATIC ABSORBER RIG

An important requirement of experimental work on absorbers is that the very high sound levels found in powerplant ducting should be attainable. This is necessary because acoustic liner performance can depend strongly on the sound level to which the liner is subjected. Considerable attention has therefore been devoted at NGTE to development of the means for producing overall sound pressure levels in the region of 160 dB in reverberant chambers and ducts. As the Establishment is well equipped with air supplies, interest centered at an early stage on the Hartmann Generator device. This consists essentially of a simple convergent nozzle producing a jet which impinges on a resonant cup situated a short distance downstream. An intense noise is produced by such an arrangement, particularly at supercritical nozzle pressure ratios when an oscillating shock system is set up. Figure 16 shows a sketch of a Hartmann Generator, together with a typical noise spectrum. The latter is seen to consist of a strong fundamental tone and a series of harmonics with a background of broadband noise. It thus resembles the noise spectrum produced by typical turbomachinery sources. In addition to development of this device as a single unit noise source for the small absorbent duct rigs, a substantial amount of work has been done on multiple Hartmann Generator arrangements for producing the very high acoustic power outputs needed for the large Absorber Facility. This is referred to again in the discussion of that Facility.

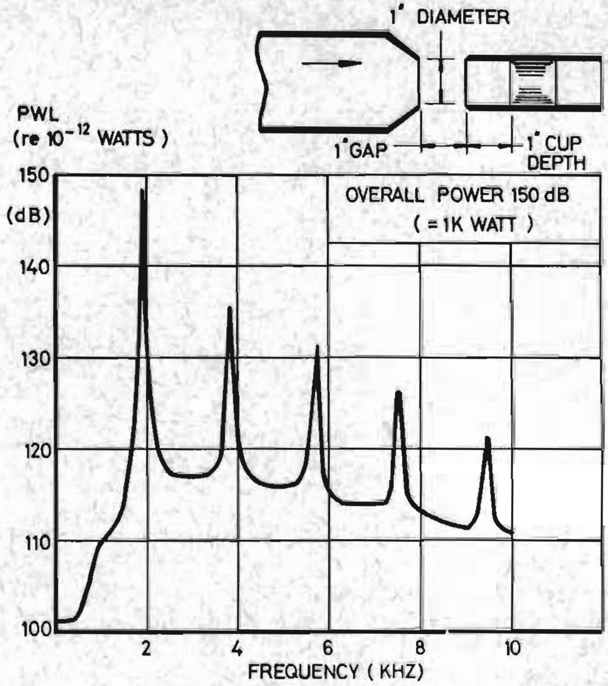


FIG. 16 ACOUSTIC OUTPUT OF 1 INCH HARTMANN GENERATOR

The conventional method used to assess the performance of liners from absorbent duct rig tests is to infer 'average' or 'effective' liner impedance from an overall measurement of the attenuation of sound through the duct. However, the dependence of liner performance upon local acoustic and aerodynamic conditions makes desirable the establishment of techniques for local impedance measurement. It is well known that the resistive and reactive components of the impedance of an absorber cell can in principle be deduced from measurements of the amplitude and phase differences between the acoustic signals at the face of the liner and at its rear wall. This 'two-microphone' method requires the development of suitable microphone probes and associated calibration techniques; the accuracy of the method being limited by the accuracy to which the phase difference can be measured. Some effort is currently being devoted to development of this technique at NGTE and Figure 17 shows an experimental probe installation in a single absorber cell.

Figure 18 shows a comparison between the attenuation of a lined duct as predicted from direct impedance measurements using the 'two-microphone' method and an earlier measurement of attenuation using microphones in the reverberation chambers. This refers to a condition of relatively low sound intensity and without air flow through the duct. There is an encouraging degree of agreement, but much work remains to be done before this technique can be applied with confidence as a standard method of measuring liner performance in realistic conditions.

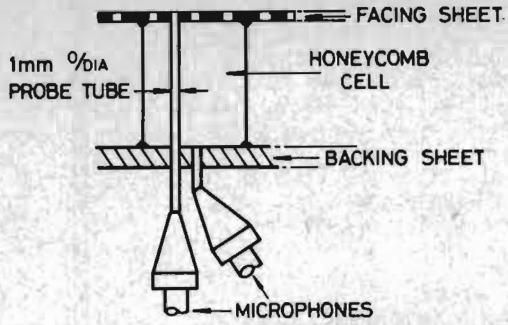


FIG.17 LINER IMPEDANCE – TWO MICROPHONE MEASUREMENT

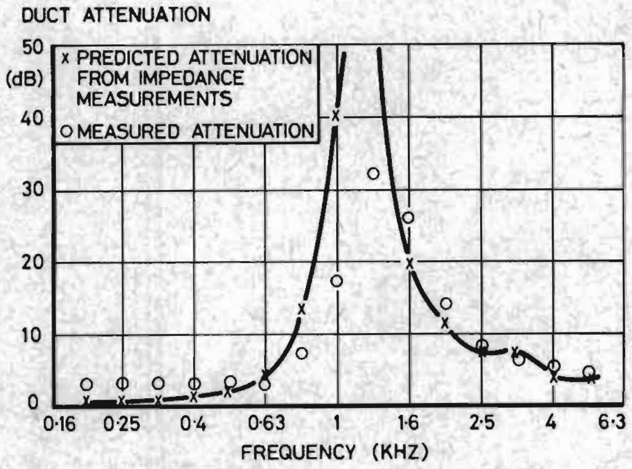


FIG. 18 DUCT ATTENUATION WITH POROUS FACED LININGS

VIII. The Noise Test Facility

With the Ansty Compressor Facility well established in service, the need was recognised in the late 1960's for further large-scale powerplant noise facilities in the UK. Particular requirements were seen to be an improved capability for studying absorbent duct liners, and a facility for testing engine exhaust systems and turbines in reflection-free surroundings. Studies made in collaboration with industry led to the proposal that a national facility meeting these requirements should be built on the NGTE site at Pyestock. The latter was selected because of the availability of suitable air supplies; construction elsewhere would have entailed substantial extra expenditure in providing air processing plant.

The initial plan was for a single multi-purpose building, with a large anechoic chamber as its central feature and adjoining rig enclosures providing facilities for tests on jets, turbines and absorbent ducts. However, subsequent design studies led to the separation of the absorbent duct rig from the main unit. This allowed the Absorber Facility, as it became known, to be provided at an earlier stage to meet the urgent need for this type of testing.

The Absorber Facility was brought into service in the Autumn of 1972, and has since been employed on test programmes on behalf of both the engine and airframe industries. Commissioning and calibration of the larger Anechoic Facility is currently in progress, the building having been completed in late 1973. Together the two units are known as the Noise Test Facility (NTF), and their operation is closely integrated with that of the NGTE Engine Test Facility which makes use of the same air processing plant.

To meet the demanding data analysis requirement posed by the Noise Test Facility and the smaller research facilities described earlier, a powerful digital Fourier Analyser system, as well as parallel filter equipment, has been provided.

The Absorber Facility

The Absorber Facility provides for the testing of absorbent materials under closely controlled conditions at realistic scale and sound intensity, and with simulation of powerplant duct airflow. The principles are the same as for the small research rig discussed earlier, with the important addition of airflow. A duct, in which various types of liner can be mounted, connects two reverberation chambers. Sound is produced at one end of the system and its attenuation on passing through the duct is measured, the acoustic impedance of the test liners being deduced therefrom.

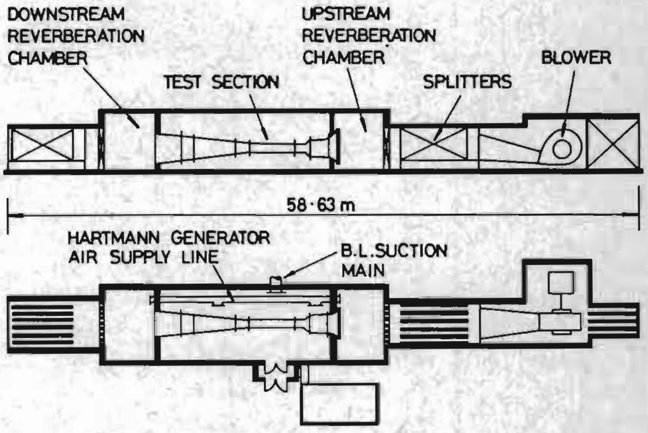


FIG.19 ABSORBER TEST FACILITY

The layout of the Facility is shown in Figure 19, the airflow direction being from right to left. Air is delivered by the centrifugal blower, via a bank of silencing splitters, to the upstream reverberation chamber. It then enters the duct which consists of a contracting entry section, a parallel test section in which the liners are mounted, and finally a diffusing section which connects with the downstream reverberation chamber. Splitter banks at entry to and exit from the Facility control external noise. To allow testing to cover the two important cases of sound propagating with the airflow (engine exhaust ducts), and against the airflow (engine intakes), the noise generating system can be placed either upstream or downstream of the duct test section. Driving air for the Hartmann noise sources is provided from site air plant. An air suction main is also connected to the Facility to allow boundary layer suction in the test duct for flow profile control. These air system connections are visible at the right-hand side of the external photograph, Figure 20, where the entry splitters and blower chamber are nearest to the camera.

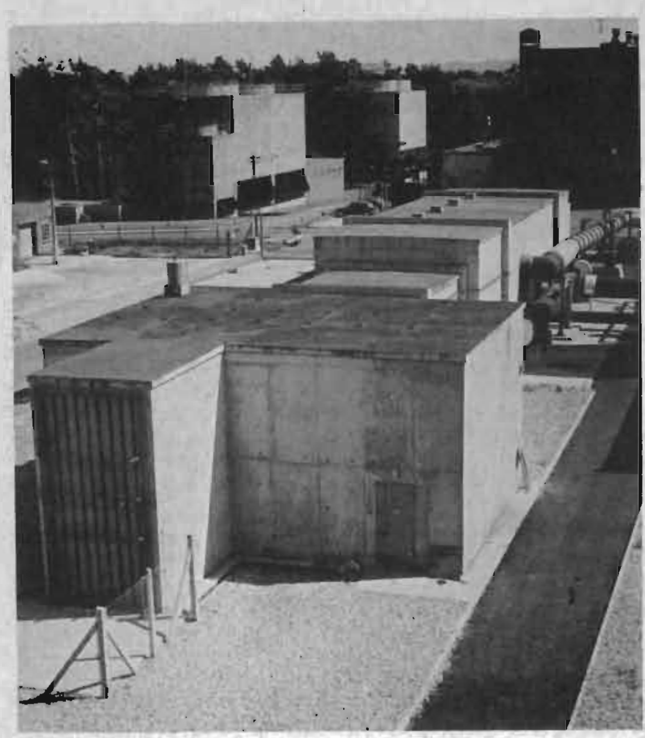


FIG. 20 ABSORBER FACILITY

The centrifugal blower which provides the duct airflow is rated to deliver 85 kg/s (190 lb/s) of air at a head of 2 m (80 in.) water gauge. In conjunction with the use of diffusion to recover test duct velocity head, this allows a flow Mach number of 0.7 to be achieved in a test section of 0.37 sq m (4 sq ft) cross-sectional area. The splitters installed between the fan and the upstream reverberation chamber serve to prevent fan noise from intruding upon acoustic measurements in this chamber when it is acting as a receiver - ie in tests when the noise generator is mounted downstream of the test duct and measurements are being made of the sound propagated upstream.

The building is of reinforced concrete construction, with the reverberation chambers isolated from the main test hall to minimise the transmission of sound via structural paths. The reverberation chambers are each 4.3 m (14 ft) long by 6.1 m (20 ft) wide by 4.9 m (16 ft) high. To meet the requirement that these chambers should pass a large airflow without undue sound losses, adjustable slats are fitted at their interfaces with the splitter banks. The slats serve to increase the reflection of sound while still allowing the necessary apertures for the passage of air.

The main hall which accommodates the test duct is 15.2 m (50 ft) long by 6.1 m (20 ft) wide by 4.9 m (16 ft) high. It is provided with built-in bed-plates and a travelling crane to facilitate the installation of various forms of test ducting. The high-pressure air supply and the suction main also enter this hall. Figure 21 is a photograph of part of the hall, showing a rectangular test section which is designed to allow the installation of up to four test panels in each of its four walls. The quick-release doors covering the panels can be clearly seen. This particular test section accommodates panels 0.5 m (20 in.) by 0.76 m (30 in.) in its sides, and 0.5 m by 0.38 m (15 in.) in its upper and lower walls. An alternative test section, currently in course of manufacture, will be of circular cross section. Also visible on the left-hand (upstream) side of the photograph is the large-diameter noise generator exhaust ducting and the smaller ducts which provide for boundary-layer suction from the upstream end of the test section.

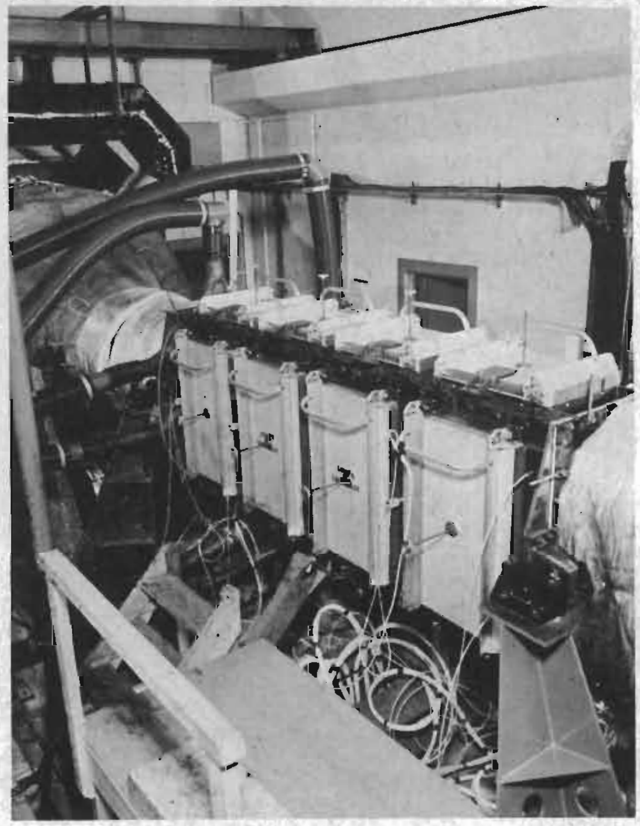


FIG. 21 ABSORBER FACILITY TEST SECTION

Reference has already been made to the use of the Hartmann Generator as a noise source in NGTE work on absorbent ducts. Design studies for the Absorber Facility indicated that to produce the very large acoustic powers required, a system using multiple Hartmann Generators would be necessary. Furthermore, because of uncertainties regarding the sound losses from the reverberation chambers with their airflow apertures, it was decided to develop for initial service a system which concentrated the noise sources nearer to the test section by placing them around a larger-diameter section of the duct instead of in the chambers. A scheme was therefore produced for an assembly of 32 Hartmann Generators, to be situated in an annular recess at a duct diameter of 1.7 m (66 in.). According to whether sound propagation with or against the flow was to be studied, this assembly would be fitted either in the approach contraction to the test section or in the diffuser portion of the duct. To avoid disturbance of the main duct airflow, the air from the generator jets would be collected by a shroud placed around each resonant cup and thence ducted away. The design acoustic power of the system was 35 kW, the object being to produce sound pressure levels of up to 160 dB in the test section.

Proof of the practicability of the concept, together with development work to optimise its characteristics, was obviously essential prior to finalising the design of the system. Aspects requiring attention were;

(i) the effect of close grouping of generators

(ii) the effect of placing them in a recess of relatively small dimensions

(iii) the effect of air collector shrouds on acoustic output

(iv) range of operation - a good range of acoustic output, with satisfactory control characteristics being required.

This work was done by Martlew and Crick$^{(22)}$, using groups of generators simulating the proposed arrangement for the Facility. Figure 22 shows one such group of three, whose acoustic characteristics were explored using the NGTE jet anechoic chamber described earlier. The nozzles of the noise generators are on the left-hand side of the photograph, the resonant cups on the right being hidden by the air collector shrouds. Also seen are the central 'needles' mounted in the cups and extending upstream into the nozzles. The addition of such needles improves the steadiness and range of operation of Hartmann Generators.

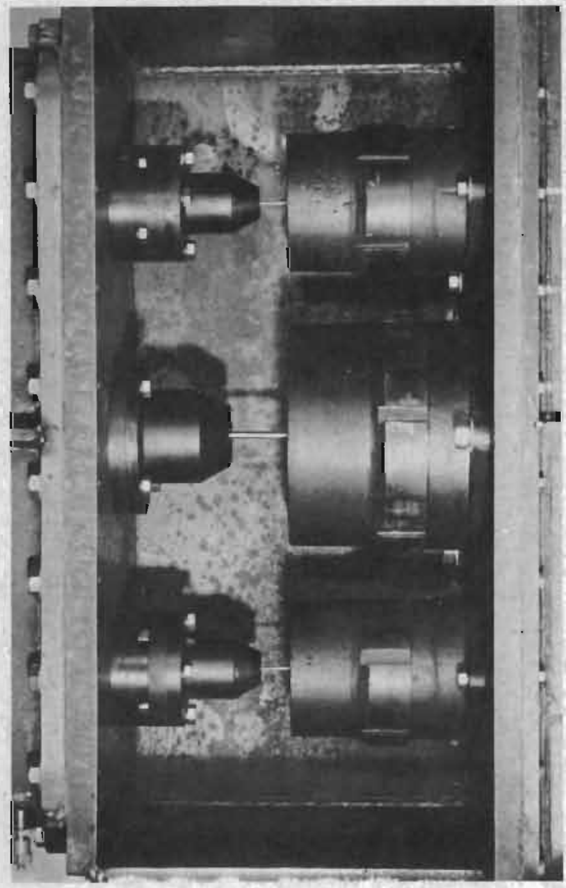


FIG. 22 GROUP OF HARTMANN GENERATORS

The work referred to above led to definition of the design of the system for the Facility. This system, which uses 24 2.5 cm (1 in.) diameter units and 8 5 cm (2 in.) units, displayed a satisfactory performance from an early stage, and Figure 23 shows the noise spectra available in the test section at generator pressure ratios of 3:1 and 1.2:1. The substantial range of operation is noteworthy, representing a ratio of acoustic power output of 100:1.

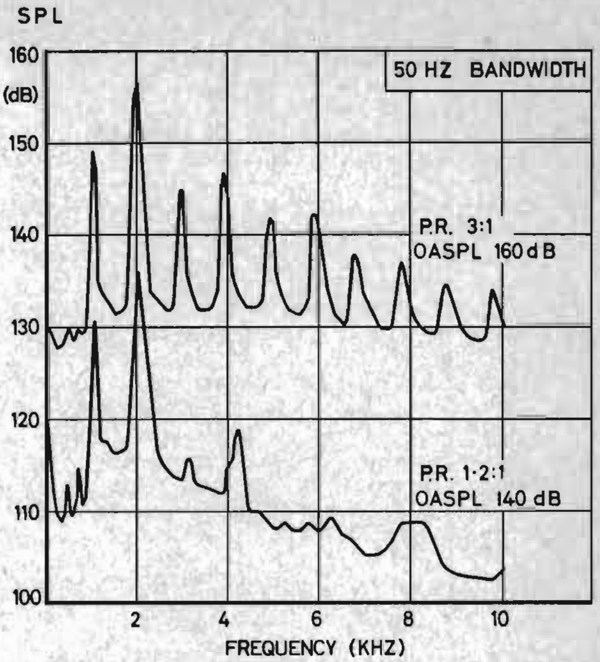


FIG.23 SOUND PRESSURE LEVELS IN TEST DUCT FROM MULTIPLE HARTMANN GENERATOR

With the Facility itself established as a going concern, further tests to explore the possibility of using simpler noise generator systems, mounted in the reverberation chambers, were done when programme commitments allowed the opportunity. It has been found that a set of three Hartmann Generators, each of 10 cm (4 in.) nozzle diameter, will provide the required sound intensity in the test section, with the following advantages;

(i) Greater flexibility of operation; moving the 32-unit generator assembly from one end of the duct to the other requires a large number of man-hours.

(ii) A first harmonic at lower frequency (about 500 Hz), useful for tests on liners designed to reduce low-frequency engine noise.

(iii) A readily tunable spectrum, by differential setting of the three generators.

The success of this recent development is likely to result in most future work in the Facility being done with the simpler generator system.

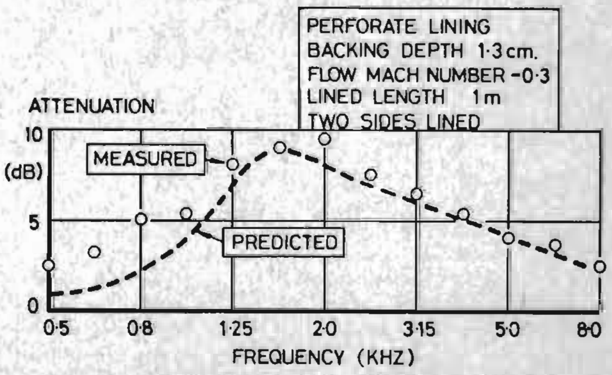


FIG.24 PREDICTED AND MEASURED LINER ATTENUATIONS

Concluding with a brief consideration of results obtained, Figure 24 presents a comparison of duct attenuation data. The plotted points represent a direct measurement of attenuation with the sound propagating against the airflow - the 'negative Mach number' case which represents the engine intake situation. The dotted curve is a prediction of the attenuation for this condition but using the liner impedance deduced from a test with the sound propagating in the same direction as the flow. The fairly close agreement suggests that, at least for some types of liner, the effective impedance derived from the latter type of test can be applied with reasonable confidence to estimate the performance of the liner with the sound propagating against the airflow. It should be noted, though, that in making such estimates it is necessary to take account of the flow velocity profile in the duct, as the result is relatively sensitive to this parameter for upstream sound propagation. This point serves to illustrate the place in absorber research of sophisticated computational techniques for applying the theory of absorbent duct acoustics to the interpretation of test data. Significant effort is being devoted to this aspect at NGTE.

The Anechoic Facility

The Anechoic Facility is intended principally for the noise testing of jets, exhaust systems and turbines at temperatures and pressures representative of engine operation. Its essential components are a large anechoic chamber, a rig cubicle with air and fuel supplies, and a silenced exhaust system capable of handling a large volume flow. The layout is shown in Figure 25 which also gives some of the main dimensions.

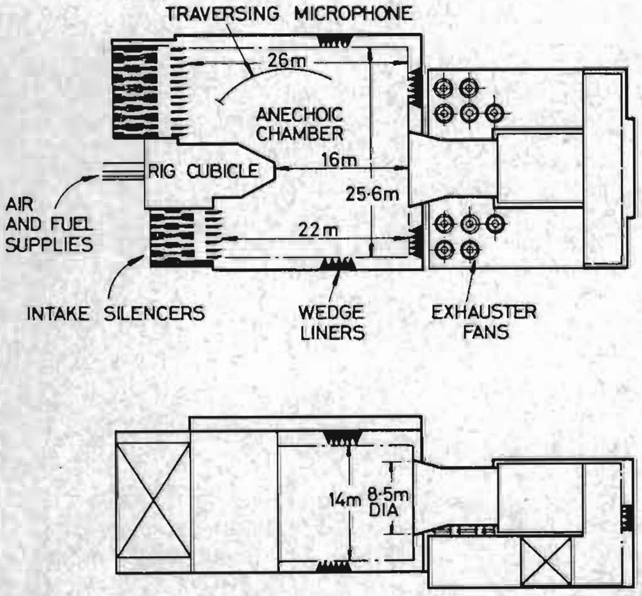


FIG. 25 ANECHOIC TEST FACILITY

The anechoic chamber, of roughly 9000 cu m volume, is lined with fibreglass acoustic wedges 0.9 m long giving effectively anechoic conditions at frequencies above about 100 Hz. Stations are provided on the chamber floor for fixed microphone masts at 15° intervals on arcs of both 6 m (20 ft) and 12 m (40 ft) radius. A traversing boom is also available, on which may be mounted microphone masts at any radius up to 12 m (40 ft).

Air entrained by the test rig jet is admitted to the chamber through banks of silencing splitters situated on each side of the rig cubicle. The flows are drawn from the chamber, as they mix, through an acoustically treated conical collector duct, suction being provided by a group of exhauster fans. The configuration of the chamber with its airflow arrangements was the subject of careful model testing prior to final design definition. Downstream of the collector duct, the exhaust flow is turned from the horizontal to the vertically downward direction at the rear wall of the building (right-hand side of Figure 25). It is then turned again at floor level to pass through two sets of silencing splitters and thence vertically upward to atmosphere via the exhauster fans. The 10 axial-flow fans can pass a total flow of about 730 kg/s (1600 lb/s), which is sufficient to ensure natural entrainment conditions for jets of 0.45 m (18 in.) diameter at choking pressure ratio. The fans can operate at suction heads of up to about 20 cm (8 in.) water gauge.

The rig cubicle is about 15 m (50 ft) long by 6 m (20 ft) wide, narrowing to about 1.5 m (5 ft) at the discharge end. The floor, which is provided with a large bed-plate for installation of rig equipment, is about 1.5 m (5 ft) below the centreline of the chamber. The axis of a typical rig can therefore lie on, or close to, the chamber centreline. A dynamometer is available to absorb the power produced by turbine test rigs. Alternatively, a small engine could be installed in its entirety.

The test rig air supply is provided from the large compressor/exhauster machines which serve the Engine Test Facility, via a 1.4 m (54 in.) diameter air main. Normally the output of one machine is used, which can be up to 90 kg/s (200 lb/s) at a pressure ratio of 3:1 or 9:1. The air enters the cubicle by two branches from the main, enabling two-stream rigs to be run if required. Preheating to about 200°C may be applied to avoid the possibility of condensation on expansion into the anechoic chamber. Silencers in the two entry pipes reduce the noise reaching the building from the plant, valves and pipework. It should be noted that although the Facility might appear to provide only for essentially 'static' testing, since no gross movement of air through the anechoic chamber at flight speeds takes place, the large available air supplies make it possible to achieve a degree of flight simulation in jet testing by surrounding the test jet with a sheath of cold air moving at flight speed. Indeed, specific programme plans already include work of this kind.

A fuel system using liquid butane is available for tests where it is desired to run at engine temperatures. The use of butane, rather than kerosene, avoids the risk of unvaporised liquid fuel contaminating the highly absorbent wedge units and thus creating a serious fire hazard in the anechoic chamber. At atmospheric pressure, butane becomes a heavy gas which would be purged from the chamber by the exhauster fans. Figure 26 shows an external view of the Facility, which is constructed of thick reinforced concrete. The air intake splitters, the central end wall of the rig room with its twin air supply pipes. and the single large-diameter air main are visible. The two horizontally mounted tanks at the left-hand side of the photograph provide storage for the butane. The brick building adjacent to the Facility houses the control room and supporting services.

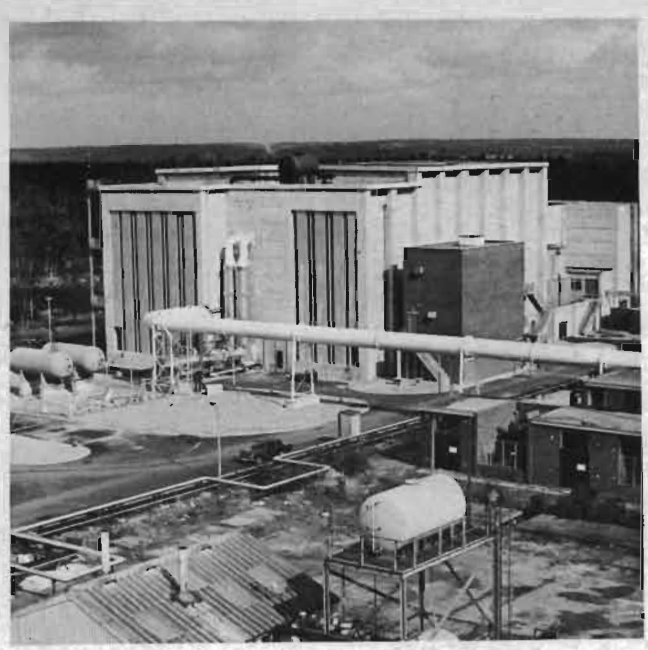


FIG. 26 ANECHOIC FACILITY - EXTERNAL

Figure 27 shows an internal view of the anechoic chamber, looking towards the 'nose' of the rig cubicle. This photograph was taken during the final stages of construction. The first simple cold jet rig used for initial testing is visible. At this stage the rig cubicle nose had not been sealed, allowing the rig air supply pipe to be seen. Also shown in this picture are several microphone masts, the vertical air inlet splitters and the microphone traversing boom which is covered with slabs of absorbent material.

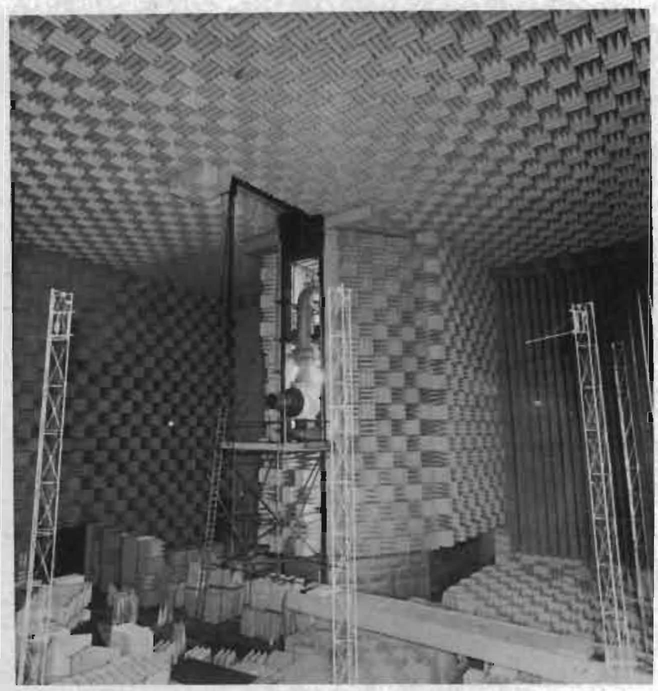


FIG. 27 ANECHOIC FACILITY - INTERNAL

Data acquisition arrangements for the Facility include logging systems for aerodynamic and other steady signals and high-quality tape recording of the unsteady signals from microphones, hot wires, etc. One-third octave on-line analysis will be possible using a parallel filter analyser, though it is likely that analysis will often be performed off-line using the digital Fourier Analyser referred to earlier.

At the time of writing (May 1974) the Anechoic Facility is still in its commissioning phase. The work up to now has been concentrated mainly upon contractual acceptance testing and calibration, and satisfactory operation with a simple cold jet rig has been demonstrated. Preparations are now in hand for the installation of a turbine rig which has already been used by Rolls-Royce for work on an open-air facility. This rig will be run at engine temperatures. For the future, it is envisaged that the Facility will be used for a variety of research and development programmes by both industry and NGTE. The work is expected to include investigations of turbine noise, excess or tailpipe noise, the performance of jet-pipe absorbent liners at engine exhaust temperatures, and jet noise both statically and with flight simulation. A fair measure of flexibility exists for accommodating both research-type experiments on standardised configurations, and work related to development which might use project hardware.

IX. In Conclusion

Reference was made in the Introduction to the comprehensive nature of the UK programme aimed at aircraft noise reduction. It is hoped that this Paper has conveyed an impression of the NGTE contribution, and its relationship with the work of industry.

In recent years the programme coordination and intramural noise research activities of NGTE have been accompanied by a considerable effort on the design and development of new test facilities. With the completion of the Noise Test Facility, this phase is now ending. The future should see the new facilities used to good effect in the vital task of evolving powerplants that combine low noise with good economics.

Acknowledgements

The author wishes to acknowledge the work of the many individuals who have contributed to the developments outlined here. He also extends his personal thanks to several members of Acoustic Aerodynamics Department who have assisted with the preparation of this Paper.

Acknowledgement is due to the Ministry of Defence (Procurement Executive) and the Department of Industry for permission to publish the Paper.

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DISCUSSION

A. Das (DFVLR-Braunschweig, Germany): In Figure 9 of the paper the effect of swirl on the noise created by a vane is shown. It is quite logical that with the swirl corresponding to the design vane angle the noise level is a minimum. In a jet engine for transport aircraft the vanes and their settings are designed for optimum efficiency in the cruise condition. During take-off and landing, therefore, even if these vanes were rotated, some part of them would generally be working under off design conditions and the noise level would not be at its minimum. So the question is whether a sacrifice in the engine efficiency at cruise can be accepted in order to achieve less noise during take-off and landing. If the characteristic typified by Figure 9 is fairly flat in the region of the minimum point, such a requirement may not be severe.

F.W. Armstrong: I should like to make two points in answering this question. First, the range of swirl covered in the experiments described in the paper was very wide. A wide range was deliberately used in this model work so that the variation of noise with swirl could be clearly established. In a well-designed engine, the swirl angle would not depart so far from the design setting during operation and therefore the change of noise level from this particular source would not be very large unless the vane design were such as to make the noise level more sensitive to incidence than with the example tested here. Secondly, as mentioned in the paper, one needs to keep each engine noise source in proper perspective. The aim of this particular series of experiments was to study the laws governing the production of noise from turbine exhaust vanes, and in this we appear to have been reasonably successful. However, the noise of any particular engine may well be dominated by other sources and, indeed, there is evidence that this is very often the case. Research aimed at identifying the various significant sources is still in progress.

G. Winterfeld (DFVLR Porz-Wahn, Germany): 1. The flow field downstream of a multistage turbomachine is well known to be of a highly fluctuating nature. Can the author comment on the effect of this on strut-produced noise or excess noise?

2. What is the efficiency of the Hartmann generators in producing noise, and how are the highly directional sound reduction characteristics of such generators taken into account, especially in the case of the 32 generator system used inside the Absorber Facility?

F.W. Armstrong: 1. At this stage, I can do little more than confirm that considerable interest centres on the fluctuating flow effects in the exhaust systems of engines. It is well known, of course, that fluctuating or turbulent incident flow is a factor in the production of noise from an aerofoil. In addition, as mentioned in the paper, it is suspected that unsteadiness in the flow crossing an engine nozzle plane could be a significant factor in the production of excess noise. Some of our current experimental work is aimed at clarifying this issue.
2. Much of our practical development work at NGTE on Hartmann generators has been directed towards maximising their efficiency in producing noise. The efficiencies now obtainable in practical systems operating in our facilities are of the order of 6 per cent, which is a good level for a noise generating device. The sound field of an individual Hartmann generator is in fact relatively uniform in directionality. But in any case, the important point regarding the use of such generators in absorbent duct facilities is that they are placed in reverberant enclosures which produce a diffuse sound field at entry to the test duct.