Problems of Noise in Helicopter Design

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M A , B SC , F R Ae S

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DR G S HISLOP (*Chairman of the Executive Council*) in the Chair

INTRODUCTION BY THE CHAIRMAN

The Chairman said that a short biographical note would illustrate the Lecturer's very wide experience Professor RICHARDS was engaged in research at the Royal Aircraft Establishment, Farnborough, and then went to the Bristol Aeroplane Co Ltd , from 1937 to 1939 He was a scientific officer at the National Physical Laboratory from 1939 to 1945 and then went to Vickers-Armstrong Ltd , where he was Assistant Chief Designer and Chief Aerodynamicist between 1945 and 1950 He became Professor of Aeronautical Engineering, University of Southampton, in 1950

Professor Richards had been awarded the George Taylor Gold Medal of the Royal Aeronautical Society , he was a member of the Aeronautical Research Council , and Chairman, Vice-Chairman and a member of several of the A R C Committees He thus has an extremely wide experience in research and in the aeronautical industry

The great need of the helicopter in one of its main roles was that it must be able to get into city centres, which meant that its noise must be acceptable to people in the cities

This posed extremely difficult problems and the Association were deeply honoured to have Professor Richards to speak on those problems

Before reading his paper, Professor RICHARDS expressed his appreciation of the honour of being invited to present a paper to the Association

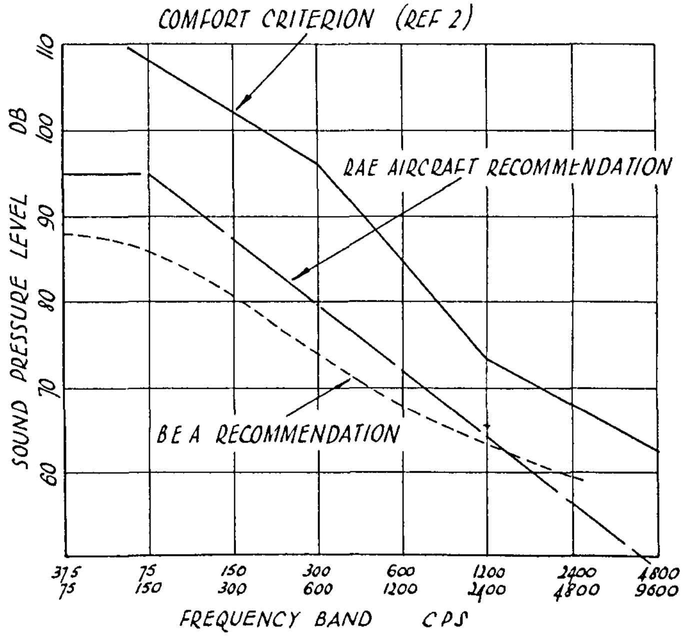
PROFESSOR E J RICHARDS

During the past few years it has become apparent that the problem of the noise of helicopters, both in its effect on the passengers and on the public near landing grounds has become quite as severe as that to be expected with normal winged aircraft, and that as the size and power of helicopters increase, the problems involved may well be even greater than with conventional aircraft which by and large are kept well away from centres of population Unfortunately so little operational experience is available on the noise of helicopters themselves that we must of necessity appeal to winged aircraft experience in order to establish the problem Before considering helicopter noise as such, it is therefore proposed to dwell a little on the difference in the two noise problems

Internal noise

As far as the passengers inside the helicopter are concerned, there is no essential difference , while it is always difficult to differentiate between noise and vibration as the real cause of annoyance and tiredness in passengers, acceptable internal noise levels have been established which can well be applied to helicopter cabin design Indeed British European Airways have already stipulated their requirements (Fig 1) of the sound pressure levels to be tolerated in the various frequency octave bands These are in fact very stringent and rather more severe than those (Fig 1) recommended by the Royal Aircraft Establishment for winged aeroplanes However, bearing in mind the relatively low horse-powers now being used, it is better to be severe at this stage rather than otherwise American ideas on the levels to be tolerated are also plotted in Fig 1 The comfort criterion curve ^{2} indicates the maximum noise levels possible before real discomfort sets in and

FIG I INTERNAL NOISE RECOMMENDATIONS



is undoubtedly a high upper limit Levels well below this are required before extended flight can give the comfort values now existing in conventional aircraft For purposes of comparison typical measured figures for two American helicopters[3] are plotted in Fig 2 as sound pressure levels in each frequency octave band It may be seen that in the medium and high frequency ranges reductions of as much as twenty decibels are required before really acceptable comfort levels comparable with the latest airliners are achieved However, the problem here is not insurmountable, two lines of attack being open to the designer, the use of soundproofing in the cabin, and the reduction of noise at source The former method is a very potent method in the high frequency range, an attenuation of twenty decibels being easily achievable with a moderate weight of soundproofing material, intelligently used The noise levels claimed by the makers for a modern helicopter project[4] with good soundproofing and a reasonably quiet propulsion system is shown in the figure, demonstrating that acceptable noise levels inside the cabin can be designed for if sufficient attention is given to the problem The reductions possible in the low frequency region by soundproofing is limited however, and recourse must of necessity be made to the reduction of noise at source, whether it be rotor noise, engine noise, jet noise, or gear noise Indeed the designer who plans to overcome all his internal noise problems by acoustic lagging is asking for trouble *Thus the internal problem very quickly associates itself with its external counterpart for which reduction at source is the only possible palliative*

	ALT FT	ENGINE RPM	BOOST IN	I A S KNOTS
BELL 47	750	3100	19	50
S 55	450	2250	27	72

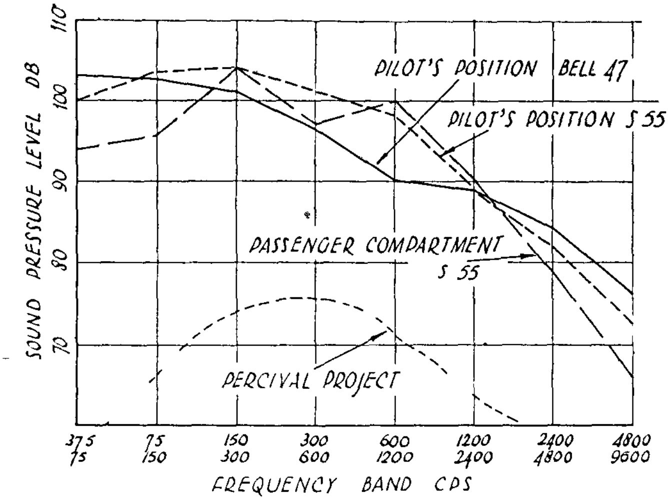


FIG 2 MEASURED NOISE LEVELS INSIDE HELICOPTERS

External noise

The establishment of a criterion for the maximum acceptable noise on the ground is a far more difficult matter, introducing a whole range of relevant factors which cannot really be assessed until real experience in helicopter operation has been obtained The helicopter's greatest single advantage is its ability to land near city centres in built up areas where buildings are often close to the landing squares Thus in any assessment of the noise levels to be tolerated, the advantage gained by the aeroplane in its use of a large airfield with a great dispersal of houses must be allowed for, even though some of the nuisance is due to aircraft passing overhead On the helicopter's credit side, however, is the much higher noise of traffic and very often the existence of other large noises such as at railway terminals, etc On the credit side also is the much smaller number of house dwellers likely to be in occupation at night near city centres and the advantageous shielding effect of the adjoining buildings The threshold of traffic noise will be higher at night in these areas than in the quiet of airports, and we can always hope for rooftop landing squares to further reduce the noise at street level Taking all things into account, and assuming that helicopter stations will be sited with due consideration of the noise nuisance, it is probable that a slightly higher noise level can be tolerated at helicopter stations than that now causing annoyance at airports, and that the relevant noise is that which will disturb appreciably during the day the office worker whose duties are interrupted by the advent of the noise

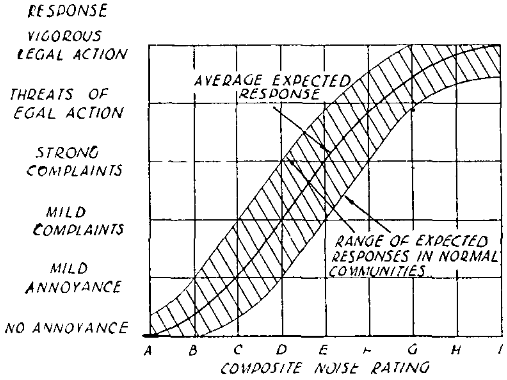


FIG 3a RELATION BETWEEN COMMUNITY RESPONSE AND COMPOSITE NOISE RATING

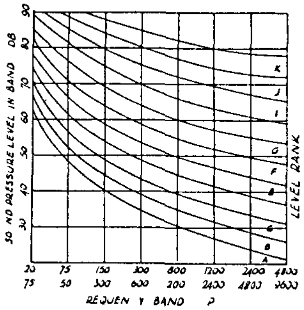


FIG 3b COMPOSITE NOISE RATING

Taking first the levels of noise that have annoyed the community in the past, Dr Bolt, of Massachusetts Institute of Technology, has put forward quite seriously[5] a series of curves (Figs 3a and 3b) indicating the response of the community in the United States to objectionable noises While there is little reason to assume that the community in England will respond in exactly the same way, and while it is admitted by those putting forward the information that many subjective elements such as whether the noise is from a favoured or unfavoured source enter into the matter, it can nevertheless be considered as the " shape of things to come " in this country also Thus in Fig 3a if we take the average expected response and accept as our standard the likelihood of strong complaints and even occasional threats of legal action, we see that a noise pressure level spectrum of the type E shown in Fig 3b is on the margin of that to be tolerated For convenience this is again plotted as curve " a " in Fig 4

If alternatively we disregard statistics of public reaction in the U S A but rather argue that complaints will arise when the actual noise levels in a private office are such as to interrupt work seriously, then Figs 5a and 5b are of significance[6] in indicating which noise levels are likely to cause objectionable interruptions in office routine If we take the optimistic view that it is only when offices become very noisy and the use of the telephone very difficult that office life will really be interfered with then we have the second curve (b) in Fig 4 (*i e*, a speech interference criterion of 60%) as a further criterion of tolerable noise levels This is probably optimistic but approaches realism more than some of the other criteria put forward at other times, particularly if windows can be always considered closed In practice the exact noise level which will raise the wrath of the multitude will vary very much with detailed circumstances but will certainly not exceed the higher of the two curves of Fig 4 For the sake of setting up a criterion to compare

FIG.4 INTERRUPTION AND COMMUNITY CRITERIA SUGGESTED AS BASIS OF PRESENT ANALYSIS

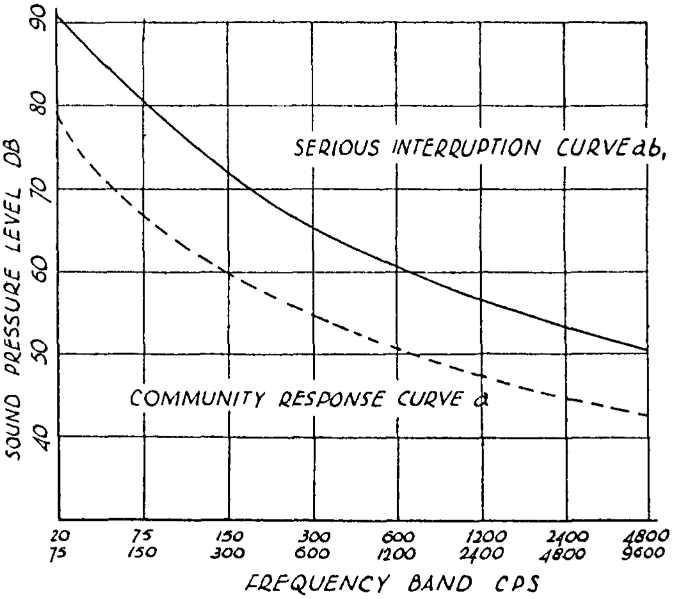
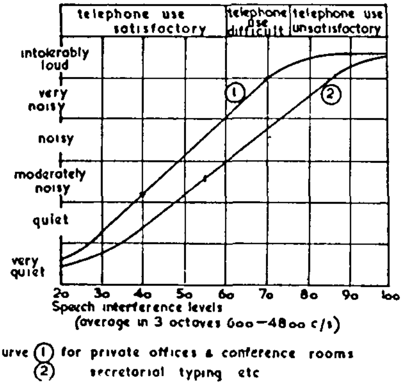


FIG 5a NOISE ANNOYANCE LEVELS IN OFFICES, ETC



our results, therefore, let us accept this upper curve as a spectrum which must be achieved if helicopters are to operate in the cities, with a view to examining later how far we are from our goal throughout the frequency range

We must now specify the distance from the helicopter where these figures are to be taken since we cannot otherwise work back to obtain design criteria for our aircraft It is suggested that the above curve should be used at a distance of 200 feet from the aircraft, since the closest offices are unlikely to be nearer Care must be taken when comparing noise figures that they are all estimated at the same distance since, as is shown in Fig 6 noise is attenuated by some 20 decibels or more as the aircraft climbs from 100 to 1,000 feet altitude or when it moves this distance away in any direction In our assessments all measured noise levels will be corrected to a distance of 200 feet unless otherwise stated An inverse square law will be used so that

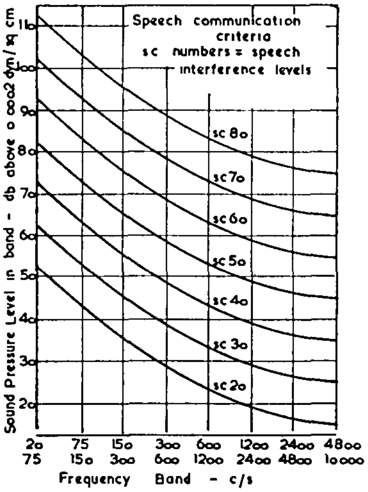
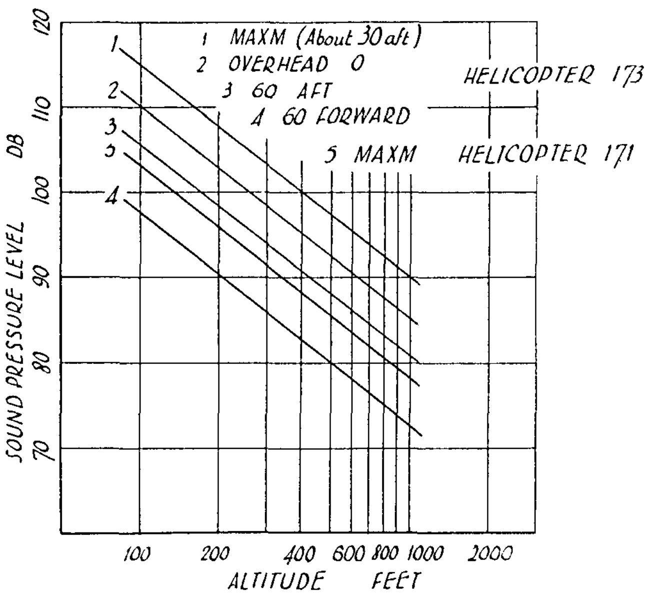


FIG 5b SPEECH COMMUNICATION CRITERIA

increasing the distance by a factor of ten for instance will reduce the noise level by 20 decibels ($20 \log_{10}10$), while doubling the distance will reduce it by $20 \log_{10}2$ (*i e* , by about 6 decibels) The attenuation with distance will be greater than this in the very high frequency bands as a result of viscous damping in the atmosphere The amount of this damping at frequencies below 1000 c p s is however very small Where possible also, measurements are given as noise spectra measured over a range of octave bands Where there are not available, overall noise measurements in terms of the sound level at a 70 phon weighting are given

To conclude this section, therefore, *we can say that in order to obtain even tolerable conditions near landing areas we must aim at noise levels below curve* (*b*) *of Fig 4 at distances of 200 feet from the rotor*

FIG 6 NOISE ATTENUATION WITH VERTICAL DISTANCE OF HELICOPTER



NOISE OF EXISTING HELICOPTERS

Measurements on existing helicopters in this country have taken two forms, the first being subjective examinations in the vicinity of city landing areas, the second consisting of spectrum analyses aimed at locating the sources of the sound with a view to its silencing In both these categories, the only information available is that given by FLEMING of the National Physical Laboratory (Ref 7, 8 and 9) though I have no doubt that many firms have taken extensive measurements on their own products Dealing first with tests made in the Houses of Parliament in connection with the South Bank helicopter station project, Fig 7 shows the *overall* sound level measured on the roof, in a committee room and on the floor of the Commons, as a Bristol 171 helicopter flew from its station at the South Bank at an altitude of 500 feet With the type of noise spectra obtained on this helicopter, these overall figures also represent approximately the octave band sound pressure levels at a frequency of about 150 cycles Thus reference to curve (b) in Fig 4 suggests that the levels in the Committee room facing the river would interfere with work quite seriously but that the levels in the Chamber itself are clearly quite acceptable Indeed the helicopter was not often heard above the background noise in the Commons itself This is not the whole story however since spectra measurements showed high noise levels in the high frequency range Thus the overall figure obtained in the committee room might correspond to a level of say 65 decibels in the 2,400—4,800 cycles octave band, a very high figure which is about 9 decibels higher than the " serious interruption " curve put forward as a basis for acceptance Thus bearing in mind that the above measurements were made at distances from the line of flight of some 900 feet, *there is need even on orthodox types with their present powers to reduce noise at source, particularly in the medium and high frequency ranges*

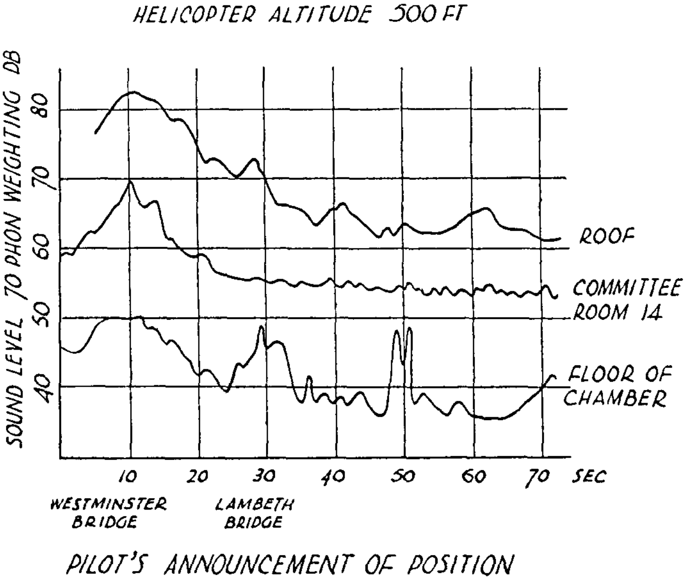


Fig 7 Helicopter noise in Houses of Parliament

Exhaust noise

A further series of tests carried out by the N P L on the Bristol 173 helicopter[8] were aimed at the establishment of the source of the greatest noise, chiefly with a view to the fitment of exhaust silencers to the aircraft In order to separate exhaust noise from rotor noise, tests were carried out first on a single rotor on the spinning tower at Bristol and consisted of both octave band and narrow band measurements There followed tests with the helicopter suspended on a gantry with the blades replaced by paddles, and continuous recording tests on the actual machine with the aircraft hovering at 50 feet, and passing overhead in level flight at heights from 100 to 1800 feet altitude The very valuable design conclusions from these tests may be summarised as follows

(*a*) The maximum noise pressure levels measured are some 12 decibels higher than on the Bristol 171 helicopter in a comparable position and was as high as 107 decibels in the 75—150 cycles per second octave band at a distance of 200 feet

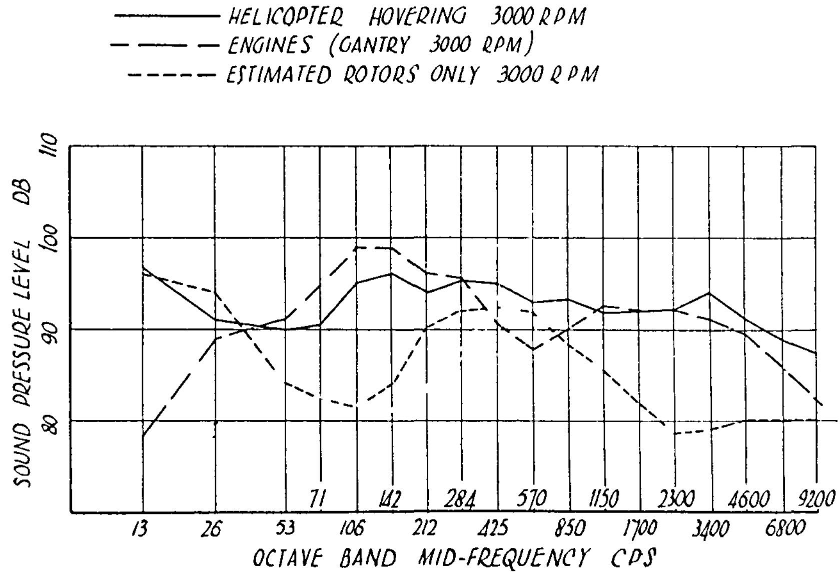


Fig 8 Noise breakdown Engine and Rotor noise

(*b*) *An analysis of the noise at source shows that this can be reduced appreciably by silencing the exhausts* From Fig 8, for instance, in which are plotted the estimated noise pressure levels from the rotor alone, that from the engine alone, and that from the actual helicopter in comparable circumstances, it may be seen that considerable noise reductions are possible by eliminating the exhaust noise In this particular instance with the helicopter hovering at 50 feet but at a distance of some 85 feet to one side, the exhaust raises the maximum noise by some 6 decibels but with the aircraft flying overhead in such a condition that the exhausts are visible they have a far greater effect For this condition of flight in which the direct effect of the exhaust raises the noise level to very unpleasant levels (an overall figure of 118 decibels was measured), the elimination of exhaust noise would probably *cause a reduction of as much as 20—25 decibels* At a distance of 200 feet and for the power used in the Bristol 173 helicopter (*i e*, two engines each developing

400 horsepower, spectra of noise pressure levels as shown in Fig 9 may be expected at a distance of 200 feet if silencers are fitted It is seen that even here much is to be required to reduce them to the levels postulated as our speech interruption criteria particularly in the medium frequency range

Direct evidence of the efficacy of exhaust silencing is derived from the comparative tests[9] on the Westland Whirlwind S 55 In these tests, spectra of helicopter noise were obtained over a range of operating conditions and with and without a specially designed Vokes exhaust silencer The general subjective noise reduction was apparently greater than appears from the noise pressure levels measured, a selection of which are included in Fig 10a It is seen that at some frequencies a reduction of 12 decibels was attainable although in other frequency ranges the reduction is disappointing Even so, calculations of the overall noise reduction indicates a general lowering by almost 10 decibels uniformly throughout the whole range of flight operations The characteristics of the silencer[10] (Fig 10b) shows a much greater attenuation on the testbed except in the fairly narrow frequency region around 90 cycles, and it is anticipated that this region can be eliminated by suitable design It is fairly obvious therefore that the noise has been reduced to the level of that of the rotor and that a less ambitious silencer could well have been used Indeed Messrs Vokes state that a suitable

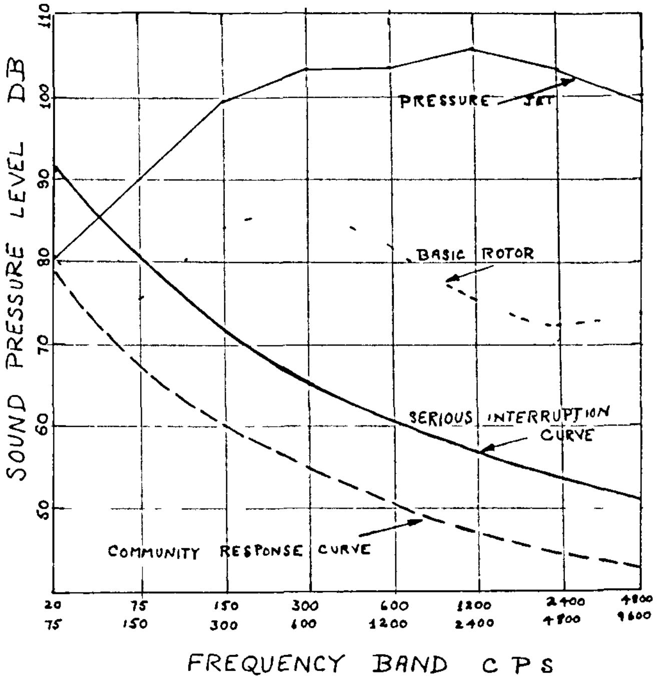


Fig 9

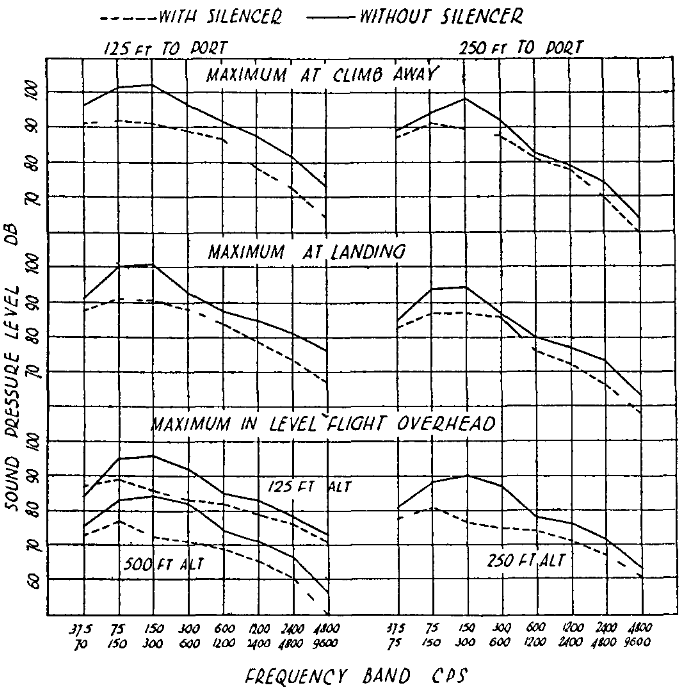
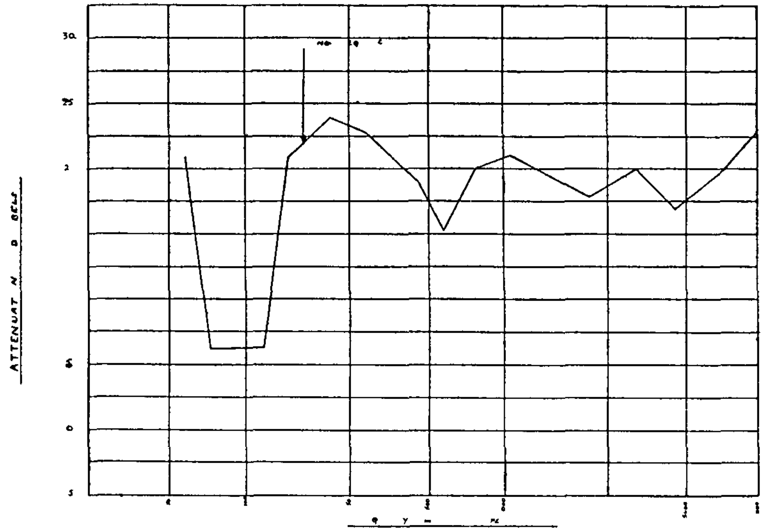


FIG 10 NOISE REDUCTION ON S55 WITH EXHAUST SILENCED



F g 10( ) VOKES SILENC R DES G D F R PRATT AND WH TNEY EN NE TYPE 3/4 IN WES LAND HE PTER TYPE WS 55 (WHIRLW ND) TES ED ON HALL SCOTT 12 CYL NDER 600 BHP ENG NE TOO production unit can be produced *for a weight of 25 pounds*, a very small penalty indeed for such a very large benefit We may conclude, therefore, *that exhaust silencers are feasible without too serious a loss of payload and that they will be fitted on future orthodox helicopters*

The above remarks apply only to piston engined helicopters As is shown from the curve of the Dart engine noise in Fig 20a for instance, a more severe problem will arise on helicopters fitted with turbine engines There is a large high frequency content in the noise, so that some viscous attenuation will take place with distance (*e g*, as occurs on the Viscount) Other than this, however, the noise attenuation possible in the low frequency region is very limited owing to the impossibility of imposing a back pressure on the engine Here again reduction at source is required either by a lagged exhaust system or by the use of a modified jet pipe system of the type described later in Fig 26 In the more serious high frequency range, where most of the noise is from the compressor, a well lagged intake will probably show some dividend Noise work is required in this field before any real conclusions can be drawn

Rotor noise

On winged aircraft fitted with propellers, the noise of the propellers themselves is as a rule greater than that from the exhaust jet, or from the boundary layer With rotating wing aircraft the same may well prove to be true in the future It is certainly true that even now rotor noise eliminates any chance of reducing noise within reach of our interruption criteria, even with the relatively small amount of power used in helicopters It is therefore, worth while to spend a little time examining the parameters involved in the production of rotor noise No systematic noise analysis of helicopter rotor noise has been carried out other than that indicated in Fig 9 and Fig 10a, so that we must fall back on propeller experience to help us out Fortunately a large amount of work has been done on propellers which suggest[11] the following generalised rules

(*a*) For a constant tip speed the overall sound pressure level increases by approximately *5 5 decibels for each doubling of the input horsepower per blade*

(*b*) For constant power the overall sound pressure level due to the propeller increases by approximately *2 7 decibels for each increase of 100 ft /sec in tip speed*

(*c*) The overall noise energy is proportional to the number of blades when the horsepower per blade and the tip speed are fixed (*e g*, two blades gives a 3 decibels higher noise level than one)

(*d*) For a constant power and tip speed the overall noise level is 3 decibels higher with a blunt tipped propeller than with a finely pointed one

The extent to which these generalisations can be carried over to the helicopter application is very hard to predict It must be pointed out, in any case, that the increases listed above arise from different causes so that these increments should be added to whatever threshold noise of that type already exists While on propellers these noises are of roughly the same magnitude, it does not follow that these will be so on helicopters

The effect of cyclic incidence changing will no doubt have some effect although it is unlikely to be confined to the low frequency region The evidence which is available suggests that the noise increase in this frequency range is not significant and can be neglected

A rough analysis of the tests on the Bristol 173[8] suggests an increase of 7 decibels when the power is increased from 200 to 350 b h p for the same tip speed This is in fact rather higher than would be expected by the propeller generalisations Thus I believe that *we can use the above criteria with caution to derive the significance of rotor changes and power increases* Clearly the amount that can be done to reduce tip speed is limited and must be weighed against loss in performance Equally however, it must be realised that the rotor tip speeds and power cannot be pushed up without the quite serious penalties listed above being incurred This is true both for the orthodox and the tip jet helicopters and must be allowed for in any new design

Whether or not the last item listed (*viz* , the effect of change in tip shape), is significant in blade design, remains to be seen Since in propeller tests, changes in tip shape generally go with changes in disc loading, the analogy is not likely to be a close one

Gear noise

In any helicopter, there is a danger of mechanical noise from one component or other While this is outside the scope of the paper, *designers' attention should be drawn to this further source of noise* While there is no evidence of serious noises of this type in this country, Fig 11[1] shows some interesting evidence of gear noise in the U S A In this instance, the noise is of far lower intensity than the exhaust noise, but once the latter is silenced, gear noise would take pride of place over and above the aerodynamic noise of the rotor In this instance the source of noise is the hammering of the gear teeth as they make contact, the measured frequencies being quite discrete and of the values expected In this figure it is interesting to note the very small amount of noise energy from the tail rotor and its essentially low frequency

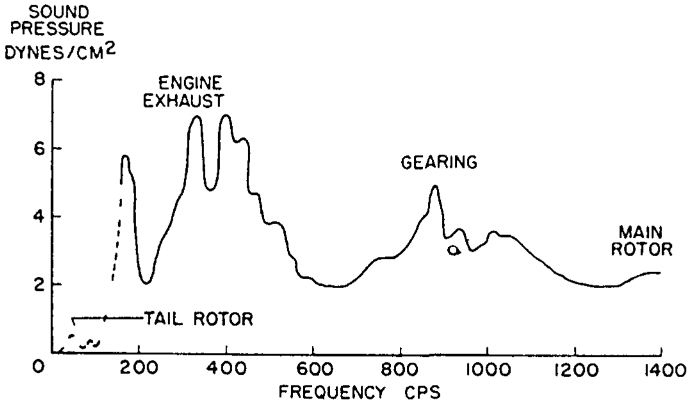


Fig 11 Noise from Helicopter in hovering frequency analysis with 20-cycle wide filter

TIP JET NOISE

The advantages of replacing the orthodox systems of rotor drive by jet propulsion units of some form are well known and need not be commented upon in this paper It is very true, however, at the moment that one of the greatest objections to their use arises from the high noise levels generated by such power units It is relevant therefore, to examine the basic differences in the characteristics of all the systems put forward These tip jets can conveniently be split up into the following four groups —

(*a*) pulse jets,
(*b*) ram jets,
(*c*) pressure jets,
(*d*) exhaust jets,

since each has its own very definite characteristics

The pulse jet, as its name implies, obtains its thrust as a series of intermittent pulses in which very high velocities are developed

The other three are continous systems, their main differences lying in their efflux velocities and in the existence on some of combustion noise The pressure jet, having the largest pressure ratio, has the highest outlet velocity, the velocity being highly supersonic or overchoked The exhaust jet has the lowest outlet velocity, the thrust being obtained by using larger mass flows and larger orifices

Sources of noise on tip jet helicopters

Before examining each type in detail, it is as well to record all the expected sources of sound on this type of helicopter since there is *no point whatever in striving for the reduction of one noise if any other is of the same magnitude and frequency* Briefly these sources arise in the main from the following

(*a*) Rotor aerodynamics and gear trains,
(*b*) static jet characteristics,
(*c*) combustion,
(*d*) rotation effects

Dealing first with (*a*) the rotor design cannot at the moment be expected to deviate greatly from that of the orthodox rotor except in so far as tip jets with large air ducts may enforce the use of thicker blades Thus the noise values attributable to the aerodynamic lift and drag of the blades will remain as before and *may be calculated from Fig 9 extrapolated to any different power and tip speed by the rules of section on Rotor noise* There is little point therefore in attempting to obtain jet noise levels appreciably below that for instance in Fig 9 for example which we may use here as a standard to compare the achievements of the various types of tip jets

Gear noise will presumably be eliminated or at least reduced by the easing of the rotor head design problem, and may be neglected as a source of noise in our deliberations provided that we appreciate that this source of noise can become serious if attention is not given to it in the design stages

With reference to (*b*), it is not the purpose of this paper to describe the nature of aerodynamic noise in jets Attention is drawn to a review of this subject[12] written by the author and published by the Royal Aeronautical

Society in their journal It is sufficient to say that aerodynamic noise emanates in three ways on tip jets

(i) As a simple acoustic source on a pulse jet of frequency equal to that of the pulse and of a mean noise level[13] given by

$$\mathrm{Db} = 10 \log_{10} \frac{1}{32} \frac{\rho_0}{r^2} \frac{c}{c^2} \left(V_{max} - V_{min}\right)^2 f^2 s^2 \times 10^9 \text{ above } 10^{16} \text{ watts/cm}^2$$

where ρ_0 is the ambient air density, c is the velocity of sound and V that of the jet of exit area s The frequency is f and r the distance from the source

(ii) On continuous jets, noise arises from the turbulence and varies for a jet as

$$\frac{\rho V^8 d^2}{c^5}$$

where V is the velocity of the jet relative to the outside air, d is its diameter, ρ is the density of the outside air and c is the speed of sound in it The constant of proportion may be obtained by reference to Fig 12 which gives a correlation between a very wide range of experimental results [14]

(iii) When, as in the case of the pressure jet and ram jet, the nozzle is well choked and a high supersonic velocity is developed aft of the nozzle,

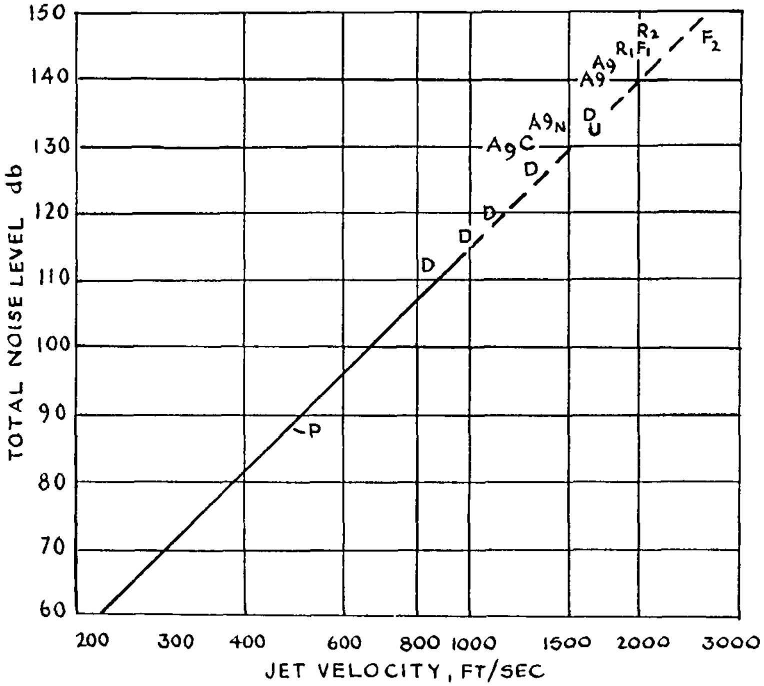


Fig 12 Total noise level at 30° reduced to R/D = 24

a great increase of noise over and above the law (ii) previously mentioned can arise from the interaction of the turbulence with the standing shock pattern There is little if any evidence of this type of noise on tip jets as yet

(*c*) *Combustion noise* takes two forms, the first consisting of the noise from the *increased turbulence in a rough burning jet*, the other arising from a *definite resonance in the jet pipe* The latter is energised by the periodic burning and is typicalised by a quite definite frequency with a wavelength of the order of the jet pipe diameter While there is no evidence of this note being present on small tip jets, there is a considerable noise increase resulting from burning generally In Fig 13 for example the noise spectra from a cold jet are compared with similar figures at comparable thrusts on a hot pressure jet of the same diameter It is seen that the spectra are of similar types, indicating that the noise increase is not confined to a single octave band and that general increases of some 7—9 decibels arise when the jet is burning fuel and is hot The overall noise pressure levels corresponding to these and other spectra at a different azimuth angle are plotted in Fig 14(a) against the total internal pressure in the combustion chamber in lb /sq in , in order to ascertain this variation with jet thrust This quantity is as good a measure of the jet thrust as can be obtained without detailed instrumentation *It may be seen that the total noise increases by some 5—8 decibels* At a measuring station at 90 degrees to the axis of the jet the increase is almost constant with increasing thrust, the noise law in either case not deviating very greatly from the V^8 aerodynamic noise law whose slope is shown for comparison * At the 22° station, the situation is more confused, the cold jet obeys the V^8 law while the hot jet shows a distinct fall away from this law with increasing thrust This is to be expected if the increase of noise is due to turbulence and poor burning The results obtained in

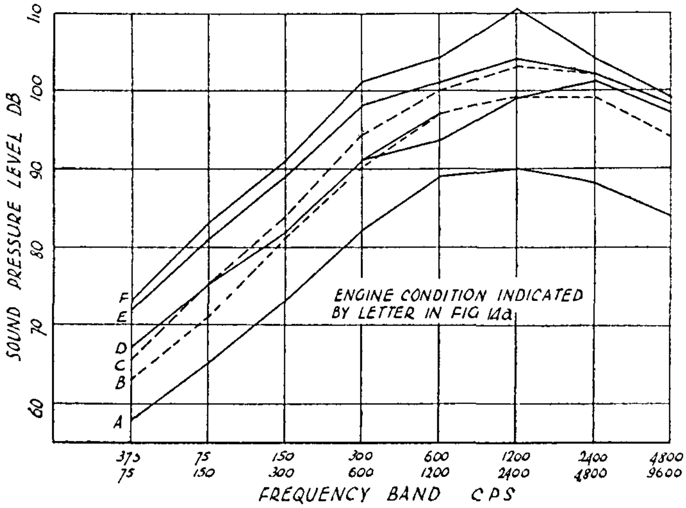


FIG 13 NOISE SPECTRA FOR HOT AND COLD JETS FOR SAME THRUST 200 ft FROM JET OUTLET

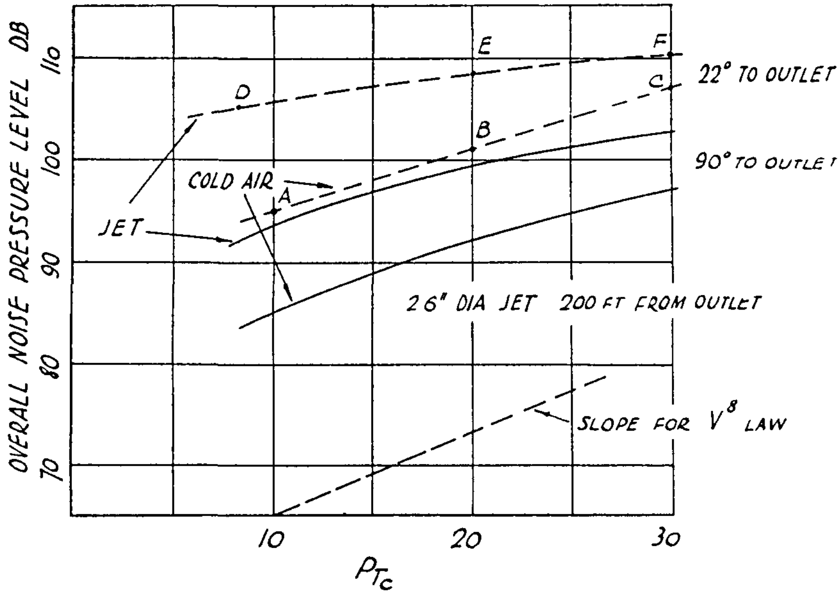


FIG 14a VARIATION OF OVERALL NOISE WITH PRESSURE RATIO

this series of tests carried out by Faireys[10] show however, very little variation with fuel air ratio so that it is difficult to attribute all this increase of noise to turbulence The best that can be said is that *in all probability combustion does have a bearing on the noise and may raise the levels by as great as 5—8 decibels* Some of this can be explained, however, by the basically different variation of Mach number in a hot compared with a cold jet, and by the fact that the density will differ so that the efflux velocity need not be the same for the same total thrust

The analysis makes no difference between the turbulence introduced into the pressure jet by bad bends, etc , as opposed to that created by combustion Noise increments of as much as 10 decibels have, however, been measured[16] on a rig in which the turbulence is increased by a double bend in the system (Fig 16) , *thus any system of suppressing combustion noise which introduces bad bends and thereby a large residual turbulence may well give increases rather than decreases in total noise levels* More work needs to be done on combustion noise, as it undoubtedly can be a major factor in noise production in helicopter pressure jet units

(*d*) The effect of rotation will be twofold, first a change in the spectrum characteristics near the rotor due to Doppler effect, the second and of more real significance the reduction in actual jet noise due to *the reduced relative velocity* of the jet stream

The first effect is more noticeable very near to the jet as a result of the

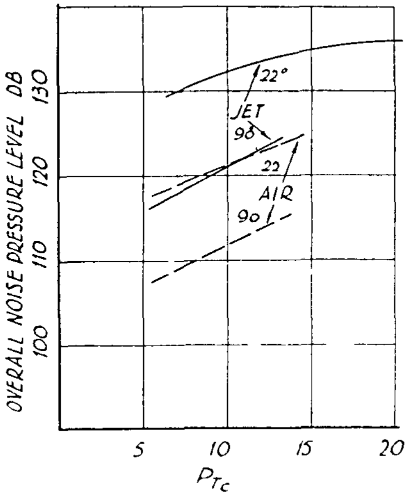


Fig 14b

Variation of overall noise with pressure ratio 3 2 in Dia Jet

fluctuating distance of the noise sources and the highly directional character of the aerodynamic jet noise The overall noise at an angle of 45° to the thrust line is for instance about 10 decibels higher than that the same distance away but at right angles to the jet axis Thus for this reason alone the sound at a given point will fluctuate by some ten decibels at one half, one third or one quarter of the fundamental rotational frequency of the rotor, depending on the number of tip units This will show itself up effectively as an annoying fluctuation in intensity At a distance of 200 ft this effect is less likely to be great and is unlikely to cause annoyance over and above that expected from the steady noise at the worst azimuth angle

The second effect of rotation, the *reduction of the efflux velocity of the jet relative to the air around it, is wholly favourable and of quite a significant magnitude* Fig 16, plotted again from the measurements made by Fleming of the National Physical Laboratory in the Fairey tests[15] shows a reduction of over 6 decibels below that measured on the static rig for a peripheral tip speed of 400 ft /sec These tests have been corrected to a constant combustion chamber pressure and so approximately to a constant thrust The noise alleviation agrees quite well (as shown in the dotted curve) with the predicted value based on the (relative velocity)^8 law, and gives us some confidence in extrapolating to lower velocity jets Thus as seen in Fig 17, a tip speed of 500 ft /sec would theoretically cause a reduction of 14 decibels on an exhaust jet with an efflux velocity of 1500 ft /sec This alleviation should be allowed for in static tests if they are to be representative of flying conditions later

In passing on therefore to an examination of the noise of the four types of tip jet as measured on static rigs, *we may therefore console ourselves in three ways*

(*a*) There is no point in reducing jet noise very much below that of the rotor system

(*b*) Noise reductions possibly as high as 5—8 decibels may be attainable

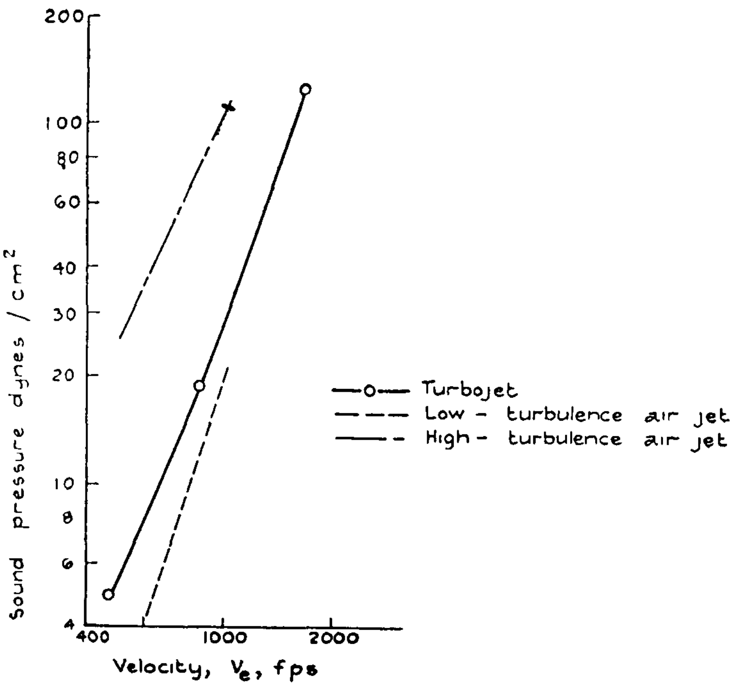


Fig 15 Effect of exit velocity on over-all sound pressures from turbo-jet and model jets

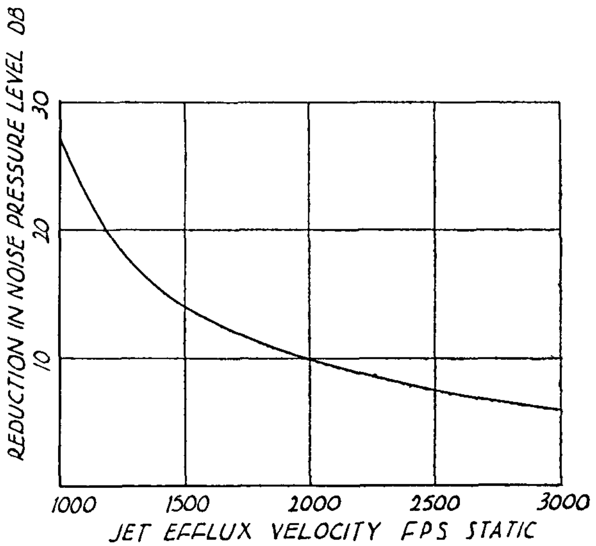


Fig 16 Effect of Rotation on noise pressure levels (overall)

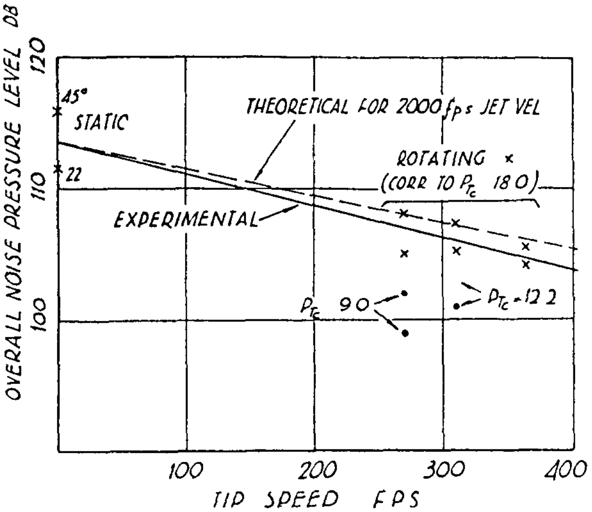


Fig 17 Theoretical noise reduction due to a 500 F P S tip velocity

if we can improve combustion in our units while not increasing turbulence

(*c*) Owing to the favourable effects of rotation on relative jet efflux velocity, static tests of pressure jets give readings which are some 7 decibels too high and exhaust jets some 14 decibels too high There may not be such a gain with the pulse jet since the majority of the noise arises from the pulse and not from the turbulent mixing of the jet

Pulse jets

Powell, in an analysis of pulse jet noise[13] has suggested that the noise is predominantly that of an acoustic source at the pulsation frequency, and that the noise may be estimated in this way with the formula on page 236

Three sets of experiments on the noise of pulse jets are available at the moment and are given in Refs 17, 21 and 13 Veneklasen[17] has measured the noise from two pulse jet engines, giving thrusts of up to 97 lb The variation of noise with frequency for this unit for two thrusts of 97 lb and 42 lb is given in Fig 18 at a distance of 200 feet at right angles to the thrust line In the same figure a similar and comparable curve of noise from the Saunders-Roe pulse jet[13] is given It may be seen that increasing the thrust in the ratio 2 25 1 gives a general increase of noise of about 10 decibels throughout the frequency range Since such an increase of thrust would involve a 50% increase in the “ maximum minus minimum ” velocity, the noise increase to be expected for a pulse jet using the formula of Ref 13 would be 20 $\log_{10}$ 1 5 (*i e*, about four decibels) The agreement with the simple source formula is thus very poor Indeed, whereas the Saunders-Roe pulse jet shows in Fig 18 a high sound pressure level at the low frequency corresponding to the pulsation, together with some high frequency noise centred around the 1000 c p s region, the American results indicate no such

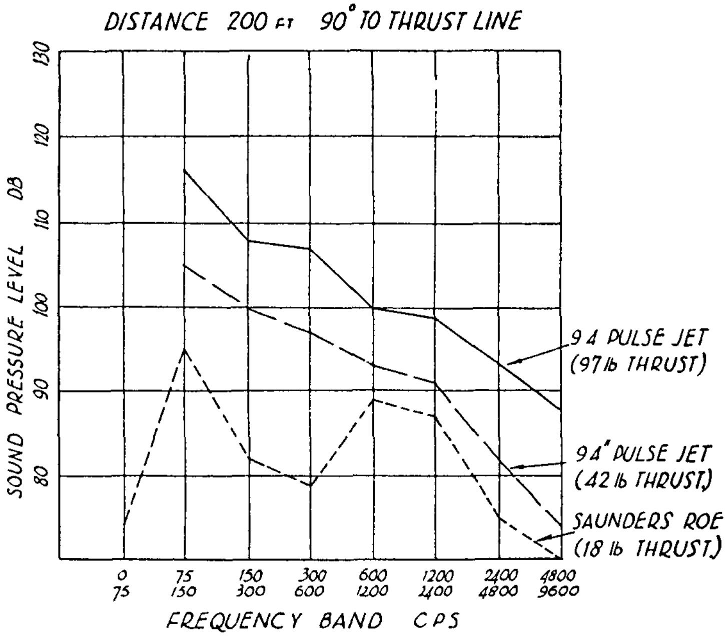


FIG 18 VARIATION OF PULSE JET NOISE WITH THRUST

discrete frequency but rather a uniform spectrum similar to a normal jet Thus it would appear that in this pulse jet at least, aerodynamic noise which arises from turbulent mixing of the stream predominates over the discrete frequency sound measured in the British tests A further series of tests[21] made in the U S A provides characteristics much nearer to those of Saunders-Roe Further tests by Saunders-Roe on a unit giving 50 lb thrust indicate noise levels not greatly in excess of that of their previous tests Thus all in all, results suggest that Veneklasen's results may not be typical of present practice and that the predominant noise remains that of the pulse In this event some silencing can be achieved by suitable matching of units in phase The noise reductions possible in this way are shown in Fig 19 taken from Ref 13

Ram jets

No information is available on the noise of ram jets Basically, however, they will conform to the same pattern as for pressure jets with the relevant pressure ratios In addition, still greater combustion noise may be present Little can be said about them at this stage which is not covered in the following paragraph on pressure jets

Pressure jets

The author is particularly fortunate in this field in being able to refer to a comprehensive test programme carried out by Fairey Aviation Ltd and

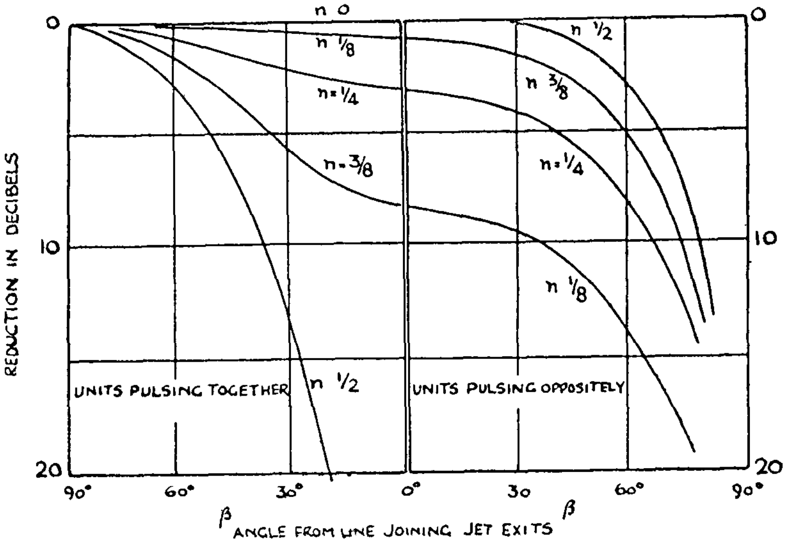


Fig 19 Theoretical reduction in radiated energy of the fundamental of the noise of two pulse jet units by mutual interference The units are spaced n wave lengths apart

by Fleming of the National Physical Laboratories (Refs 15 and 18) Reference has already been made to the experiments aimed at establishing the effect of combustion and rotation Other tests carried out in this series consisted of an extensive examination of

(1) the effect of varying the fuel air ratio in the combustion chamber and

(2) a whole range of silencing devices

There is little purpose in referring to the former tests in detail since the results showed that for a constant combustion chamber inner pressure (and so a nearly constant thrust) the overall noise levels remained practically constant over a very wide range of fuel air ratios The conclusion to be drawn is therefore that the optimum fuel air ratio may be chosen purely from the considerations of performance efficiency within very wide limits of fuel air ratios As pointed out by the firm these results must, however, be treated with much reserve Any variation in the fuel air ratio makes a large difference to the temperature and thus the density of the mixture Even for constant thrust, a large variation in velocity will occur which would be expected to give a large noise variation It may well be that variation in combustion noise is obscuring the real effect of the variation in fuel air ratio More work is again required to clear up this difficulty

Silencing devices on jets

It may be seen from Fig 21 that the maximum noise from a pressure jet of 3 64 in diameter with a thrust of 280 lb is about 106 decibels in the 1200—2400 c p s frequency band at a distance of 200 ft at right angles to

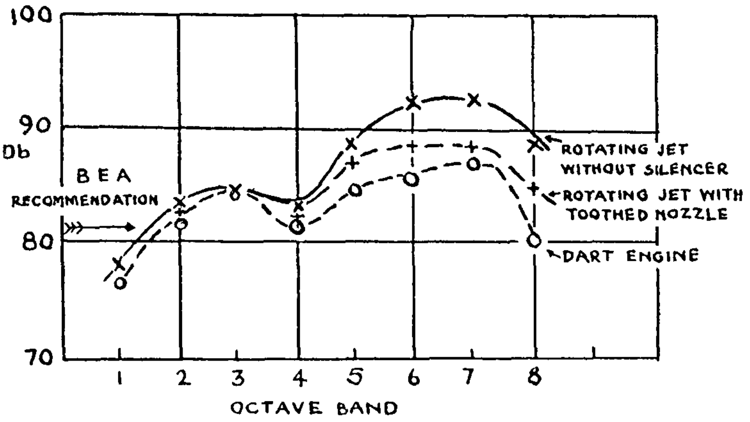


Fig 20a Noise level on Fairey pressure jet

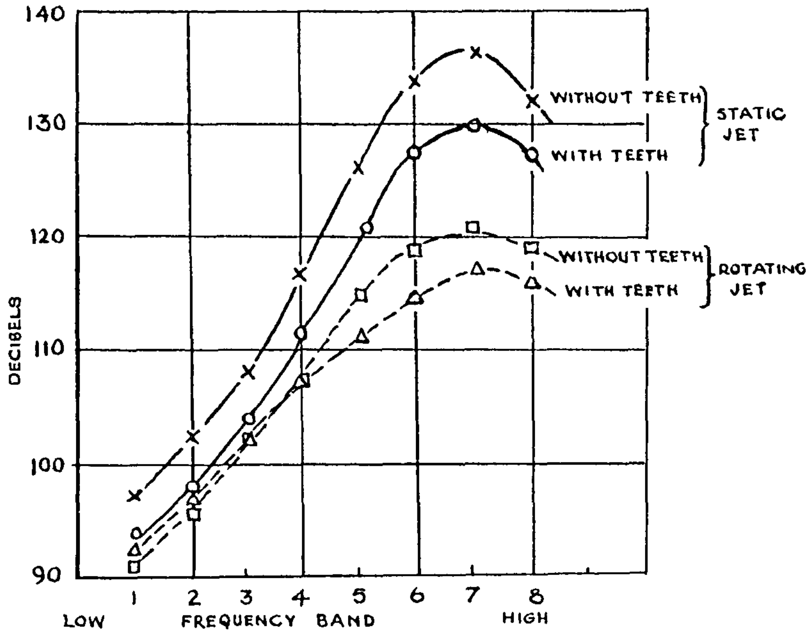


Fig 20b Noise levels from static and rotating pressure jets at comparable powers and at a distance of about 6 ft from nearest point in jet periphery

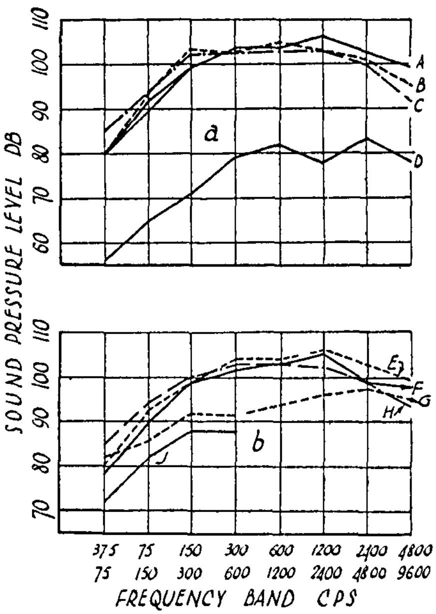
the thrust axis This level will be increased by some 6 decibels with the full number of units, decreased by some 7 decibels as a result of rotation and will be increased somewhat by the directional pattern and the eventual increased thrust normally to be expected in propulsion unit development *The pressure jet curve of Fig 9 may, therefore, be regarded as a not pessimistic measure of the noise at 200 feet distance on an actual tip rotor helicopter using pressure jets* The need for silencing is therefore paramount, although there is little point in reducing it below the threshold (of the order shown in Fig 9) of the rotor noise Without attempting to be precise, this would indicate the need for an attenuation of about 20 decibels at frequencies above about 600 c p s In the Fairey tests the various approaches to aerodynamic noise silencing explained in Ref 12 have been tried and varying results obtained

The first system tried was the Cranfield teeth As shown in Fig 20 the first set of tests[12] on a small rig gave favourable results, showing noise reductions of as much as 6 decibels at some frequencies The frequency range, in which this reduction was obtained was satisfactory and the results were quite promising Unfortunately the second set of tests[18] on a larger rig using the 3 64 in diameter unit did not bear out the promise of the earlier tests Fig 21 includes a typical spectrum with a toothed nozzle corrected to a distance of 200 ft and measured in the 22° direction to the thrust axis of the jet, roughly the direction of greatest noise It is seen that in these tests little if any gain was obtained while a 2 5 per cent thrust loss was incurred for the same combustion chamber pressure The overall noise levels for all the silencing devices tested are tabulated for two azimuth angles in Fig 22 These again bear out the negative results of this latter test with the toothed nozzle It may be that in the second set of tests the combustion noise, swirl, and initial turbulence were different from that in the early tests Whatever the reason, it emphasises the *need in all work* on jet noise to carry out all tests *under conditions as close as possible to the full scale application* Even so, these negative results of the second set of tests are in agreement with some American tests on a jet installation and suggest that in order to obtain reductions with the Cranfield teeth, very great care must be taken that in obtaining in this way the effective extension of the peripheral length of the jet, the turbulence introduced must not be so large as to nullify the gain so obtained

In addition to the Cranfield teeth, the Fairey Aviation Company tested a large range of devices aimed at silencing and shown in Figs 23 and 24 One type, the gauge extension, has been shown in laboratory experiments to eliminate nozzle superpressure and to reduce noise at supercritical pressure ratios As may be seen in Fig 21(b), there is again no reduction The other type of silencing arrangement, the fluted nozzle, has also been disappointing and as shown by the noise spectrum in Fig 21(a) and by the overall noise level in Fig 22 little if any reduction is obtained

The development of this idea to its ultimate conclusion gives the cross tail nozzle shown in Fig 23 It will be seen that this design does in fact give a reduction in overall noise of some 9 decibels Its use as shown, however, cannot be considered since the thrust loss of 12% incurred is much too large a penalty to pay for such a noise reduction Further work is therefore needed to examine in far greater detail the reason for this thrust reduction The answer probably lies in the detail design of the unit and the fact that the nozzle may well not flow full so that the velocity at the outlet is not uniform In this case the nozzle area would effectively be constricted thereby raising the maximum velocity and incurring heavy thrust losses

In view of the success of the fluted jet pipe as a silencer in other fields, it is worth dwelling on this type of installation for a moment Both initially at the University of Southampton[12] and in a highly developed form at Rolls Royce Ltd [19] *this type of nozzle has shown great promise* The Southampton tests showed good reductions at high pressure ratios comparable with those of the pressure jet The type of fluted nozzle tested in full scale at Rolls Royce (Fig 25) has not, however, been tried out at pressure ratios much greater than the critical value for choking There is little reason, however, to suppose that the suppression will vanish at high pressure ratios , *it is thus well worth while persevering with this type of arrangement in helicopter pressure jet design* in spite of the pessimistic results so far obtained The size of the flutes and their spacing have been examined in considerable detail and a method has been put forward by Greatrex giving the relationship between flute spacing and the frequency of maximum attenuation By this means noise *reductions of 9 decibels have been obtained* in the most needed frequency ranges on large jet engine installations It is probable that similar gains may yet be obtained on helicopter pressure jets by very careful design of the whole unit



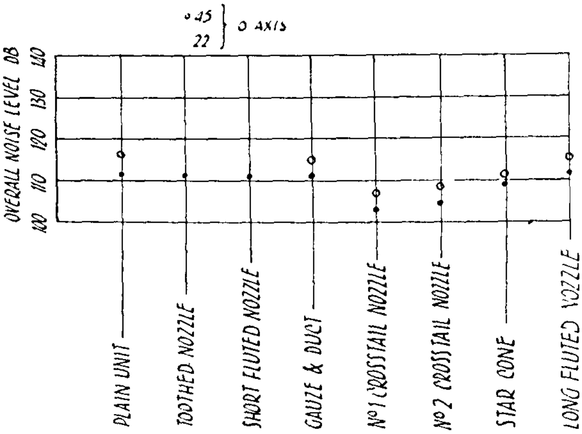
	DEVICE	THRUST LOSS %
A	PLAIN NOZZLE	0
B	FLUTED NOZZLE	28
C	TOOTHED NOZZLE	25
D	ENGINE ONLY	-
E	PLAIN NOZZLE	0
F	GAUZE & DUCT	3
G	CROSSTAIL NO 1	12
H	STAR CONE	5
J	PLAIN GAUZE	3

FIG 21 NOISE REDUCTIONS DUE TO SILENCING DEVICES OF FIG 23

Other silencing systems

A new form of pressure or exhaust gas jet unit has recently been investigated at the University of Southampton[20] with a view to reducing noise by a fundamental change in pressure jet design In practice this unit might appear in the form shown in Fig 26 in which the gas is discharged through an annular nozzle over a tailcone The noise source in this case, being the region of turbulent mixing, is reduced greatly in length[20], thereby allowing the velocity to fall without the creation of such large eddy systems as with a normal circular jet Thus the low and middle frequency noises are reduced, possibly at the expense of very high frequency noise Figs 27a and 27b show a comparison extrapolated to 200 feet distance of the noise pressure levels between a normal circular 2 in diameter jet and an annular unit of the

FIG 22 OVERALL SOUND LEVELS WITH VARIOUS SILENCERS DISTANCE 200 FT



types shown with a 6 in mean diameter and with the same outlet area and thrust as the circular jet The lower comparison is for a combustion pressure ratio of 2 16 (*i e*, for a slightly choked jet M = 1 11) This might well be taken as typical for the exhaust jet type of unit *It is seen that in this case there is a noise reduction throughout the whole frequency range which is as high as 16 decibels in the most annoying frequency region and is as much as 10 decibels in the very lowest frequency range* At combustion chamber pressure ratios comparable with that of the pressure jet, in which the flow is well choked, the reduction is maintained as shown in the upper figure and is again as high as 16 decibels It is felt that by corrugating the outside of the periphery, thereby still further increasing the frequency at which the suppression disappears, still further reductions can be obtained

It must be pointed out in assessing these early thoughts on such a unit that these tests have been made with cold air with little initial turbulence and no combustion noise It may well be that a full scale experiment would prove once again the danger of relying too closely on laboratory experiments

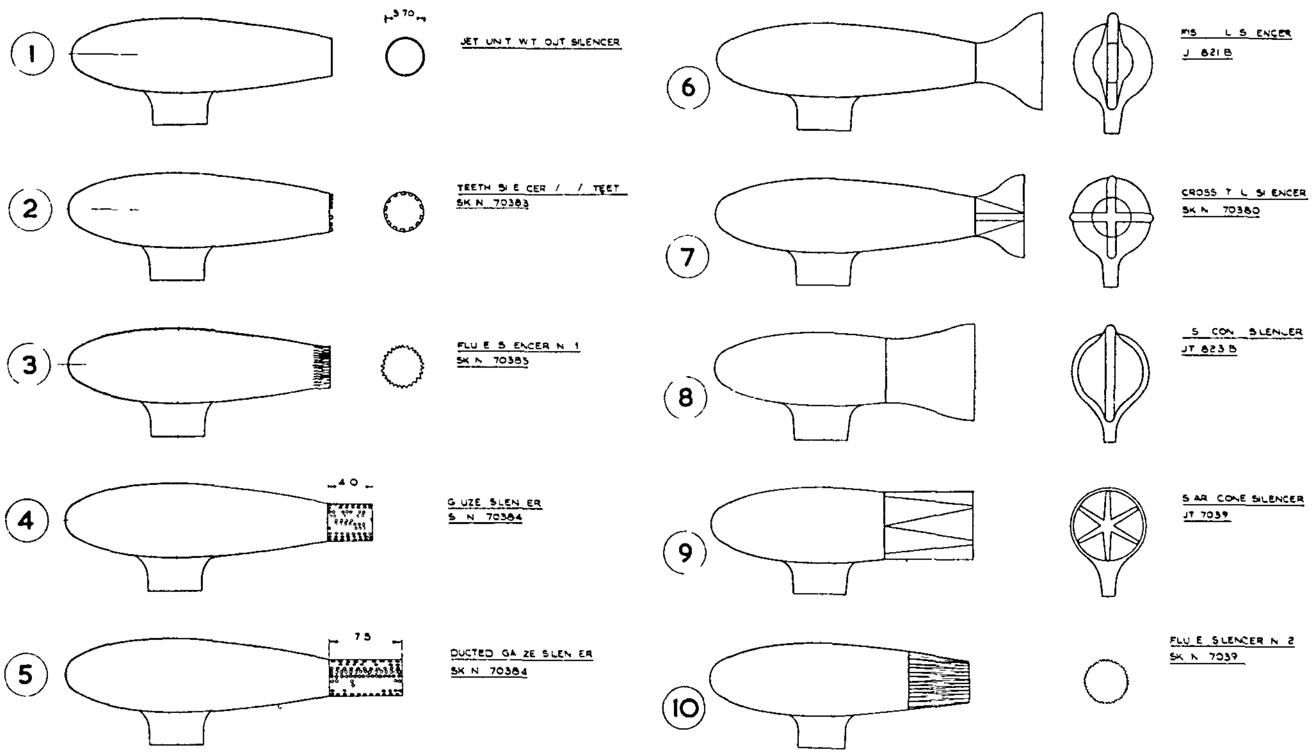


Fig 23 *Silencing Devices for Combustion Chamber as tested in Third Range of tests on the Static Rig in White Waltham*

the method of approach is, however, fundamentally sound , furthermore better combustion can probably be obtained with such an internal arrangement It is hoped therefore that helicopter designers will express their views on the feasibility of such a novel pressure jet While no experiments have been made to measure the thrust on such a unit, it is thought that provided the flow is suitably directed over the rear cone, the thrust loss will be small One objection to the system is the larger diameter incurred in the arrangement tested There is no virtue, other than that of simplicity, however, in the circular periphery The basis of the noise attenuation is the need for a long thin jet, and this can be obtained in many ways *For instance, a long elliptic peripheral nozzle may well fit into designers' present ideas*

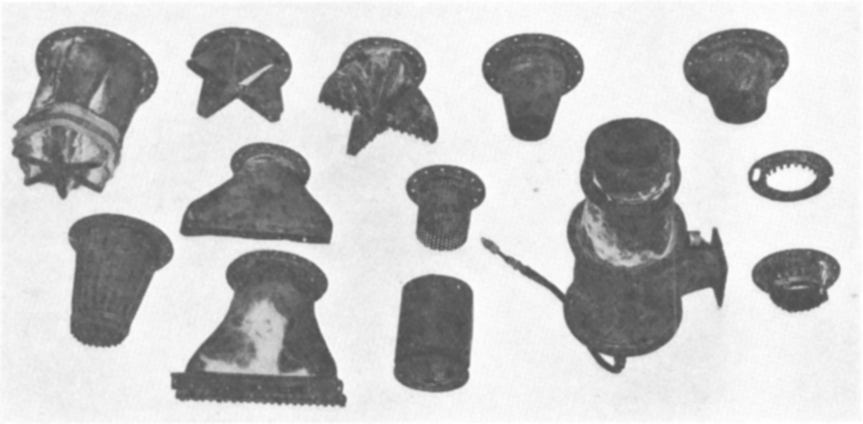


Fig 24 The Range of Silencing Devices tested

The inevitable development from the above is the long two dimensional jet unit shown in Fig 28 In the form shown *with a thin corrugated outlet, the noise pressure levels should be well down to the rotor noise level* Very considerable performance advantages may also be obtained if the jet is turned down through a substantial angle, say 40 to 50 degrees, the blade lift in this case being augmented by the gas flow in a ratio inversely proportional to the relative blade velocity *The advantages of this system both from the noise and performance angles suggest considerable promise for the future,* noise reductions throughout the frequency range of as much as 20 decibels being feasible

Exhaust gas jets

In emphasizing earlier in the paper the increase of noise energy as V^8 as opposed to the V^2 law for the thrust increase, *the need to reduce jet velocity,*

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* The actual magnitude of the V^8 noise at any specific combustion chamber pressure is not of significance

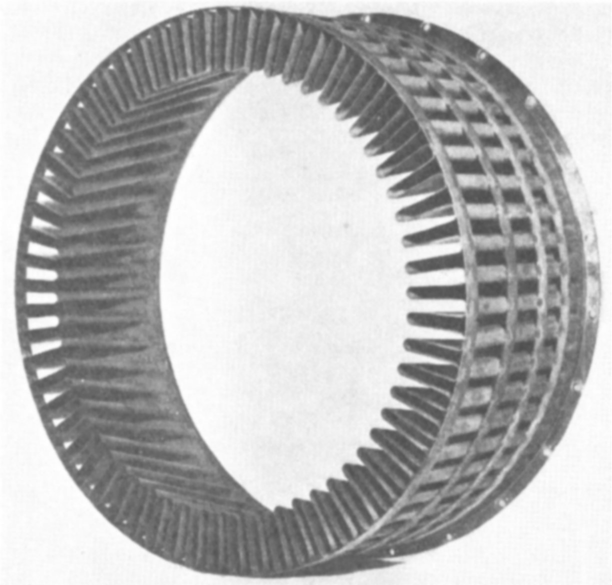

Fig 25 Corrugated Nozzle Rolls Royce

even at the expense of larger gas units seems clear Thus from the noise point of view, *the low pressure gas unit must be considered with very great favour*, although there are clearly many disadvantages in installation Since in this type of power unit the source of noise is the same as previously discussed, there is no need to dwell further on methods of noise suppression This unit with a nozzle of the type described in the last paragraph, should allow noise levels well below those of the rotor to be achieved with very little development The only additional danger arises from the likelihood of sharp bends in an installation handling such large mass flows with a consequent high residual turbulence

Needless to say, any of the silencing schemes put forward in the previous paragraph apply equally to this type of unit Furthermore the possibility that such reductions may not be needed is indicated in Fig 2 which shows

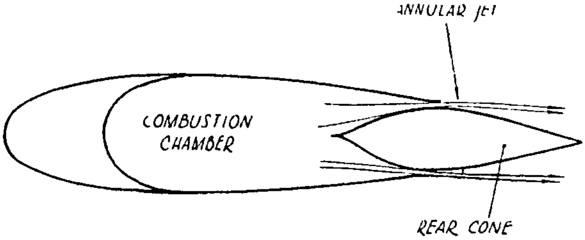

Fig 26
Annular Pressure Jet

the estimated noise levels inside a projected helicopter using this type of power plant It is seen that the levels approach quite closely the B E A internal noise requirements even with single windows in the cabin and with no silencing devices It is, of course, too early to comment on this estimate The conclusion can be drawn, however, that with careful design, *the problem of noise on tip jets is not insurmountable and is more likely to be overcome than is that of aerodynamic rotor noise*

DISCUSSION

There is a danger that in amassing all the data in this lecture, insufficient emphasis has been placed on the design lessons to be learnt from the results For the sake of convenience they are therefore listed below I hope that such a presentation will be taken in the right context and that full recognition will be taken of the very early state of the art of noise prediction on helicopters

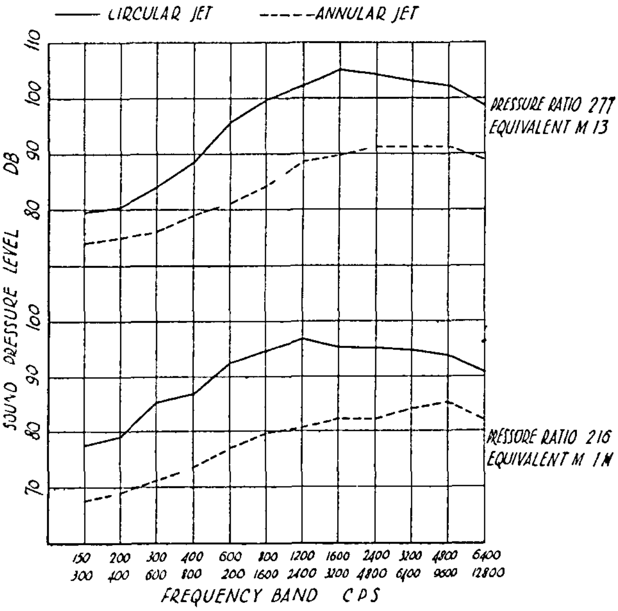

Fig 27 Noise reduction with annular pressure jet (Southampton tests)

CONCLUSIONS

(1) No clearly defined criteria of noise nuisance is available, the factors involved being too varied to allow real assessment until practical experience is obtained The curves of Fig 4 may be taken as the best guide for the time being

(2) Orthodox helicopters present noise problems already Much of this can be overcome by exhaust silencing

(3) The aerodynamic noise from the lift and drag of the rotor are such

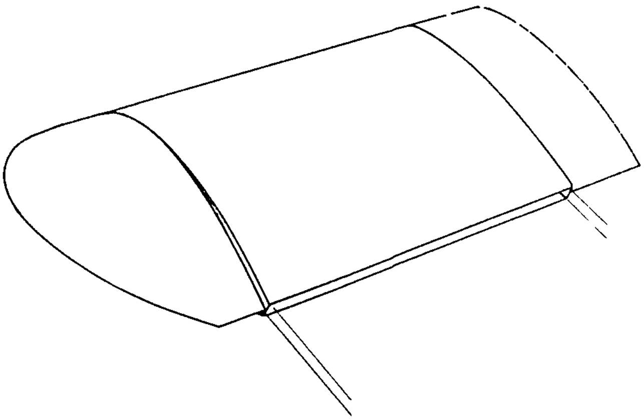

Fig 28 (Two-dimensional pressure jet)

as to eliminate the possibility of really great noise reductions without reductions in tip speeds The best way to predict this noise at the moment is by extrapolation of Fig 8 using the principles of page 236

(4) Gear noise can predominate once exhaust silencing is achieved if mechanical design is carelessly carried out

(5) Exhaust silencing can be achieved for very little weight and can give noise reductions down to the rotor threshold

(6) Turbulence and combustion can be very great noise producers on tip jets, the exact magnitude being at the moment uncertain Care should be taken in design to eliminate all turbulence makers

(7) Much must be done to reduce the noise of ram jets and pressure jets to acceptable levels The pessimistic results so far obtained on silencing devices should not be given too much weight and further tests made

(8) The fundamental changes in pressure or exhaust gas units put forward in the paragraph on *other silencing systems* should allow noise levels comparable to that of the rotor to be easily achieved

(9) Rotation gives a favourable noise change of a magnitude depending on the tip speed of the rotor and the efflux velocity of the gas

(10) The exhaust jet is the most promising tip jet from the noise point of view, no serious noise problem being envisaged The pressure jet can probably be made acceptable by the extensive development of noise silencers

In conclusion I wish to thank the Ministry of Supply, National Physical Laboratory, Fairey Aviation Co Ltd , Saunders-Roe Ltd , Vokes Ltd and Hunting Percival Ltd for allowing the publication of data The opinions expressed, however, are strictly my own I wish to thank my colleagues at the University of Southampton, in particular Dr FRANKLIN, for their help in the preparation of this paper

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Discussion

The CHAIRMAN said they had heard a fascinating discourse on a very difficult problem and they were greatly indebted to Professor RICHARDS for preparing this comprehensive paper on a subject which was very timely to all helicopter firms and was of particular value to his own, the Fairey Aviation Company

Mr F B Greatrex (*Rolls-Royce Ltd*), said that he had thought there would be no noise problems with helicopters when he had heard that helicopters had been operating into and out of Norwich at 3 0 a m for a whole winter without any trouble Perhaps that was because the buildings nearby were offices and nobody was sleeping in the neighbourhood

Although he knew little about the helicopter field, he believed that the paper would be a classic reference for some time

In the curve showing the sound level at which serious interruption occurred, he had been surprised to see that the curve rose continuously right down to the lowest frequencies Although this curve followed a typical background noise down to about 300 cycles, he would have thought that at the lowest frequency it was about 20 decibels above a typical background It might be that a loud low-frequency noise was not