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NOISE RADIATION FROM V/STOL AIRCRAFT

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NOISE RADIATION FROM V/STOL AIRCRAFT[†]

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Abstract

This paper presents a detailed evaluation of design factors affecting noise annoyance by V/STOL aircraft. Community noise annoyance is quantified on the basis of recent analyses of survey data, and the implications on V/STOL design discussed. The effect of fundamental design choices on noise levels is analysed. The principal noise sources, and therefore the optimum noise control measures, are a function of disc loading. It is found that increase in rotor scale gives a substantial benefit in subjective levels at the lower disc loadings. Rotor noise source mechanisms are discussed in detail and the dominant effect of the unsteady aerodynamic input to the rotor demonstrated. Data on the effects of recirculation on noise is presented. Two approaches for low noise V/STOL seem to be feasible. These are the low disc loading open rotor, and a ducted fan with substantial duct attenuation treatment. The principal noise control methods for each approach are given.

I. Introduction

Several writers have pointed out the existence of a "short haul gap" in the present transport system(1, 2, 3). This seems to be most satisfactorily filled by small V/STOL aircraft, operating relatively frequently from small airports close to the communities they serve. The concept offers many benefits. Airway and ground link congestion is seriously affecting many major airports. Intelligent use of V/STOL aircraft via a local airport concept could substantially reduce congestion at major airports both in the air and on the ground. Simultaneously such aircraft would provide improved service and thereby attract increased passenger traffic. Aircraft types considered in this paper are generally aimed at this concept, which appears to imply an all up weight of 50, 000 lb. and about 100 movements per day.

To be effective these smaller V/STOL ports must be close to the communities they serve. V/STOL capability allows airports to be small, reducing land costs. But this very closeness to the community exacerbates the noise problem to a considerable degree. Furthermore, the aircraft must overfly at comparatively low levels the communities they serve, causing additional potential for noise annoyance. Therefore noise places severe restrictions on V/STOL design.

Community annoyance by aircraft noise is an established sociological fact, which thus requires consideration at the earliest possible stage of the design of an air transport system, including both aircraft and airport. The first practical compound helicopter, the Rotodyne, flew around 20 years ago. Although in many ways this was an excellent aircraft and far ahead of its time the noise levels from its tip jet propulsion were too severe to allow its use. The success of newer V/STOL designs will be governed to a large degree by their success in reducing noise to acceptable levels.

Aircraft can be quiet, as evidenced by the successful U.S. Army Y03A Quiet Observation Aircraft, reported to sound like "the rustling of leaves in the wind". Indeed several methods for quieting aircraft are well known - for instance reducing rotor tip speed, lowering jet exhaust velocity, and providing acoustic linings. The designers problem is to incorporate these known techniques for noise control, while retaining viable aircraft economics.

However, solution of the V/STOL noise problem requires simultaneous consideration of at least three factors; reduction of aircraft noise at source, operational procedures for minimum noise, and airport design and location. This is analogous to the classical source-path-receiver approach to all noise control problems. In the present paper attention will naturally be directed primarily at the source, but some account must be taken of the path and receiver links in the noise annoyance chain. No consideration will be given here to the role of operational procedures in aircraft noise reduction. This is a potential benefit of V/STOL aircraft, since more flexibility in operation is possible. The noise advantages of steep climb and descent paths are well known.

Thus the paper commences with a review of community response to aircraft noise. Quantification of the annoyance is discussed, and the implications for V/STOL airport planning and for V/STOL aircraft analysed. Sources of noise from V/STOL aircraft are then reviewed, and their comparative significance in various forms of lift and propulsion system is examined. From this the effect of fundamental design choices can be analysed. Source mechanisms are then considered in detail, and based on this methods for the control of V/STOL noise are discussed. Conclusions are summarized at the end of the paper.

II. Community Response to Noise

In aircraft noise studies, Perceived Noise level, in PNdB, has been adopted as a standard measure of the subjective annoyance of a noise(4). There are many possible objections to this particular measure, and many different forms of PNdB now exist. In practice, for typical airport operations the details of the particular subjective measure used have little significance in the final annoyance estimate. Two simpler measures, involving fre-

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quency weighting of the noise, are the "A" and "D" (previously "N") scales which are shown in Figure 1.

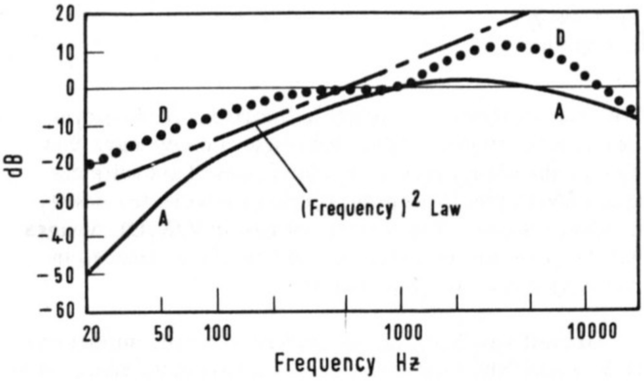


Figure 1. Subjective Weightings for Noise

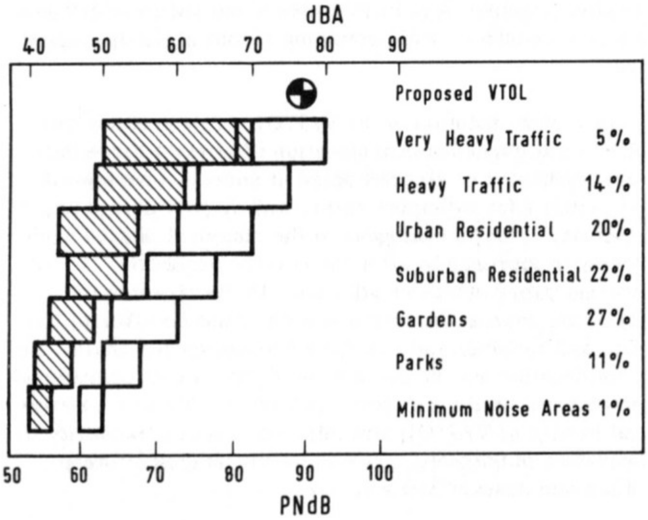


Figure 2. Typical Urban Noise Levels (based on data of Ref. 5)

For aircraft noises all three scales give equivalent rank order results, but do differ by a mean level given approximately by

$$L_{PN} = L_A + 13$$

$$L_D = L_A + 7$$

so that a sound level of 80 dBA would be roughly 93 PNdB. Typical levels for various urban environments are shown in Figure 2, based on the results of a 1961 survey in London given in the Wilson report(5). Blocks give the 10% and 90% limits of level, for both night and day. Thus sound levels were recorded within the ranges shown for 80% of the period surveyed. The percentages on Figure 2 refer to the proportion of survey locations in each noise category. The data on Figure 2 was taken using an "A" weighting scale and is converted to PNdB using the relation given above.

Subjective scales are the result of laboratory tests aimed at measuring the apparent loudness (or annoyance) of a noise. How these scales correlate with the annoyance of a real community is another question. This question can only be answered via a social survey. Many such surveys have now been carried out. How their results should be interpreted is still a matter of argument. A particularly complete review of the results of various surveys has been given by Ollerhead(6). In British work it was found that the Noise and Number Index (NNI) correlated well with annoyance. This is defined by

$$\text{NNI} = \bar{L}_{PN} + 15 \log_{10} N - 80$$

$\bar{L}_{PN}$ is a mean peak daytime level and N is the number of aircraft flybys per day, introduced to provide some allowance for the number of times people were noise annoyed. The constant 80 was introduced so that zero NNI correlated with zero mean annoyance. Originally Perceived Noise Levels below 80PNdB were ignored in calculating NNI, but recent work has shown how lower levels must be included, and this is done in the American Noise Exposure Forecast (NEF) which can be written as

$$\text{NEF} = \bar{L}_{EPN} + 10 \log_{10} N - K$$

where $\bar{L}_{EPN}$ is an average "effective perceived noise level" and K is a constant, equal to 88 for day, and 76 at night. Comparisons show that, very roughly,

$$\text{NNI} = \text{NEF} + 10$$

and NNI will be used exclusively in the remainder of this paper.

Use of any scale requires that it be correlated with community annoyance. Recently, at Loughborough University of Technology, Ollerhead(6) has exhaustively reviewed survey data, and produced the graph of annoyance against NNI shown in Figure 3. This shows the percentage of population falling into six categories of annoyance as a function of NNI. It is based on the assumption of a normal distribution for the annoyance scores, and correlates well with existing data. Based on this, the proportion of the populace "very annoyed" or worse, by aircraft noise can be defined and is shown in Table 1.

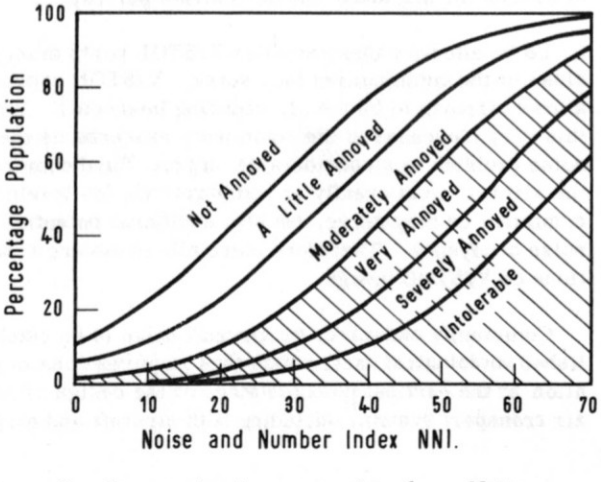


Figure 3. Community Annoyance Levels vs Noise and Number Index (based on Ollerhead(6))

NNI Range	% of Population
0 - 10	2.3
10 - 20	6.7
20 - 30	15.9
30 - 40	30.9
40 - 50	50.0
50 - 60	69.1
60 - 70	84.1

TABLE 1 Percentage of Population Very Annoyed, or worse, as a function of NNI.

Consideration of community response has many implications for V/STOL systems. Several writers have considered typical noise environments and concluded that a level of 90PNdB will be adequately quiet. Figure 2 shows that 90 PNdB is virtually on the upper limit of the urban noise environment, only around 2% of locations exceeding this value. At 100 flights per day 90 PNdB would produce a value of 40 NNI. Figure 3 and Table 1 show that close to such an airport at the 30 - 40 NNI level 30.9% of the population will be "very annoyed" or worse.

Aircraft Type	NNI	Contour Radius (ft)	Sq. miles Affected	People Annoyed
All	40	500	0.03	0
Helicopter		A	0.20	600
	30	1380		
		B	1.26	2,000
	20	3610		
		C	6.35	4,300
	10	8330		
		D	23.48	5,400
	0	16660		
			Total	12,300
STOL		A	0.18	600
	30	1360		
		B	1.17	1,900
	20	3500		
		C	5.86	3,900
	10	8020		
		D	21.60	5,000
	0	16000		
			Total	11,400
High Frequency Aircraft		A	0.08	250
	30	980		
		B	0.22	350
	20	1710		
		C	0.59	400
	10	2860		
		D	1.44	300
	0	4570		
			Total	1,300

TABLE 2 Noise Annoyance Parameters for Various V/STOL Aircraft.

90 PNdB at 500 ft. has been taken as a convenient reference point in this paper, but the acceptability of aircraft producing this level of noise is obviously questionable, and further reductions in source level are most desirable. For the assumed level of aircraft movements zero NNI would correspond to a noise level at the airport boundary of 50 PNdB. Such levels of noise would clearly result in hopelessly uneconomic aircraft. Thus the noise problem reduces to one of balancing the benefit of the airport operations against the disbenefit (primarily noise) to the surrounding community. This concept has been explored by Richards(7).

In order to quantify the annoyance (disbenefit) further a simple point source model of the airport has been taken. This will be adequate to describe VTOL port annoyance and should indicate leading features of STOL port noise. For a point source model all noise contours will be circles centred on the centre of the airport. The distances of various contours have been calculated for three aircraft types.

a) conventional helicopter
b) a STOL aircraft
c) a possible aircraft with noise predominantly at high frequency

Each aircraft is assumed to cause 90 PNdB at the 500 ft. radius airport boundary. The one-third octave spectra assumed are shown in Figure 4. The calculated contour distances include allowance for the propagation losses of the noise over its path. Based on these contour distances the ground area exposed to various NNI levels (based on 100 movements per day) can be calculated, and from this the percentage of population annoyed determined via Table 1. If this percentage is multiplied by the area an effective "annoyance area" is found for the aircraft. This is finally converted into number of people annoyed by multiplying by the population density (typically 10,000/sq.mile for an urban area in Britain).

The results are shown in Figure 5 and Table 2. Several features emerge. In each case the largest contribution to annoyance is actually from the comparatively quieter noise zones which include a very much larger number of people. This is a vital point. The natural tendency in planning is to focus attention on the high noise areas. But it can be seen that elimination of annoyance in these areas - for instance by non-residential zoning - will have very minor effects on the annoyance of the community as a whole.

Figure 5 also shows a major difference between aircraft types. The helicopter contours are more widely spaced than the STOL aircraft, especially at the lower contour levels, while the high frequency aircraft has remarkably closely spaced noise contours. The reason for this lies in the increased effect of atmospheric attenuation on noise at higher frequencies. At 10,000 Hz sound is attenuated at over 20dB/1000 ft. under standard atmospheric conditions. Spectra for the conventional aircraft studied here attenuated at around 7dB per doubling of distance, while the high frequency aircraft attenuated by over 10 dB per doubling. Thus considerable noise benefit can be achieved by choosing higher frequency noise sources. This is an obvious possibility for reducing noise annoyance.

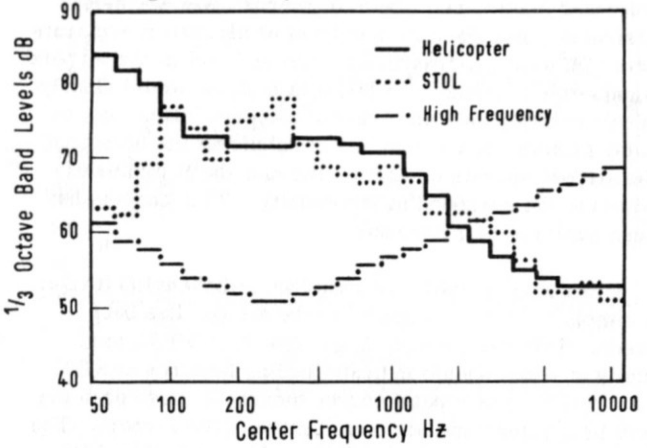


Figure 4. Aircraft spectra used in contour estimates.

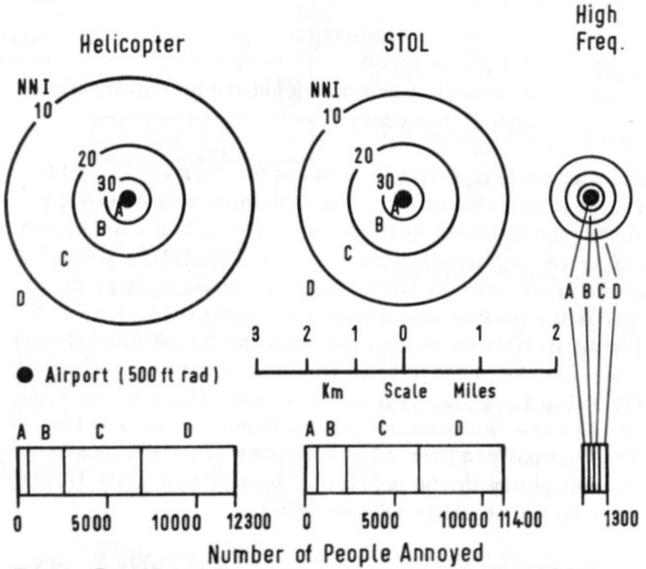


Figure 5. Noise Contours and Annoyance for Aircraft of Figure 4.

However the results of Table 2 must not be overemphasised. They are based on the NNI formulae of Figure 3 which are in turn based on average survey data. There are several indications that averaged survey does not give a complete picture. Recent work by Waters and Bottom(8) at Loughborough University of Technology has shown that communities with low levels of background noise due to traffic are more annoyed by a given aircraft noise level than are communities with a higher level of background noise. It appears that it is the intrusiveness or noticeability of the noise which governs annoyance. This has been quantified by Robinson(9). In urban areas, high background noise levels are induced by traffic which has a predominantly low frequency spectrum not unlike the helicopter or STOL noise spectra (a) and (b) above. Thus these types of noise would be less noticeable in this environment, while a high frequency noise source might be more intrusive. In quieter suburban areas any aircraft would be noticeable so that the potential benefits of a high frequency design become more pronounced. Equally no account has been taken of overflight cases in the above model. It appears that V/STOL aircraft will be limited, for air traffic control reasons, to a maximum of 2500 ft. altitude. At these altitudes ground noise levels may well be around 75 PNdB, so that comparatively little annoyance is to be expected in urban area overflights for any aircraft. Suburban overflights would lead to some degree of annoyance, and there could be some advantage in a high frequency noise source choice. For overflights the number term in the noise and number index assumes increased importance, since V/STOL aircraft will normally diverge in all directions from the airport, leading to a reduction in number of flights observed as distance from the airport is increased. Equally, a reduction in aircraft noise source strength or an increase in its attenuation will reduce the number of flights observed as well as the actual levels, so that there is a double benefit to be gained by noise control at source.

A final point to be noted is that reduction of noise at source brings almost proportionate reduction in total annoyance. A 10 dB reduction in noise causes nearly a tenfold reduction in number of people annoyed. However, this effect is due to a contraction of the low level noise contour areas. Close to the airport site a 10 dB source reduction only reduces noise annoyance by a factor of about two for the cases taken here.

This discussion also demonstrates the crucial importance of choosing proper noise criteria for community noise purposes. It must not be forgotten that the fundamental objective is to minimise noise nuisance, and not simply noise level. Virtually all standards at present work to a noise level criterion. With such certification requirements possible benefits of high frequency attenuation are not fully recognised, so that the manufacturer has less incentive to explore them. All aircraft considered in Table 2 cause 90 PNdB at the airport boundary and all are therefore rated equal via present certification ratings. But the annoyance ratings are very different. The definition of noise criteria closely related to actual community annoyance appears to be an important prerequisite for successful planning against aircraft noise annoyance, and could have a major effect on aircraft and propulsion system design.

Factor Change in Intensity	dB Value	Subjective Effect
2	3	Barely distinguishable
4	6	Noticeable
16	12	Pronounced

TABLE 3 Effect of Changes in Acoustic Intensity.

III. Effects of Design Parameters on V/STOL Noise

A fundamental feature of acoustics is that subjectively effective acoustic changes require orders of magnitude changes in engineering parameters. This is illustrated by Table 3 and has several important implications. First of all, it will be observed that acoustic calculations which are correct to a factor of 2 will be indistinguishable from exact results. Secondly, only order of magnitude changes in engineering parameters will produce noticeable acoustic effects. Thus once a design layout is complete, the acoustic output is largely determined. Conventional design improvement via parameter optimization may be worth 10 or 20% in mechanical performance improvement, but will be quite valueless acoustically. Thus, in designing a muted aircraft it is essential to include acoustic considerations at the outset of the design.

There are three major sources of noise from propulsion machinery which can be isolated. Firstly, there is the discrete frequency noise - the whine of the jet, or the popping of a helicopter rotor. Secondly, there is the broadband noise associated with the rotating machinery. This can be identified on a helicopter as a repetitive swishing noise. Thirdly, there is the pure jet noise, familiar as the roar of conventional jet aircraft. Each of these sources can be described in considerable detail, but this detail often hides the fundamental dependencies and it is thought worthwhile here to give, first of all, a very broad discussion of the effect of fundamental design parameters on these sources. More detail discussion is reserved to a later section.

The mathematical results for rotor noise radiation have been covered in previous papers(10, 11, 12). In simplified form the theoretical results for discrete frequency radiation may be written

$$p_D^2 = T \frac{T}{A} \frac{M^2}{r^2} f_D \qquad (1)$$

where p_D^2 is the mean square sound pressure level, T is rotor thrust, A disc area, M effective rotor Mach number and r the distance from the hub. f_D is a complicated Bessel function sum term. It is a weak function of rotor parameters and observer position, but it is found to depend critically on the strength of the fluctuating forces acting onthe rotor, being proportional to their nondimensional squared magnitude.

The broad band noise radiation from the rotor is found to behave as(12, 13, 14, 15)

$$p_B^2 = T \frac{T}{S} \frac{M^2}{r^2} f_B \qquad (2)$$

Where p_B^2 is the broad band mean square level and S is the blade area. As before f_B can be a weak function of many parameters, but is a strong function of unsteady inflow, proportional again to the square of the nondimensional random force levels.

The other major noise source from engines is the jet exhaust, which essentially obeys the Lighthill(16) U^8 law.

$$p_J^2 = A \frac{U_J^8}{r^2} f_J \qquad (3)$$

where U_J is the jet exit velocity. Some modification to this law occurs at jet exit speeds above M=2 or below M=1, as shown empirically by Bushell(17).

It is possible to incorporate a very large number of detail effects into the f functions of the above equations. However for the present purposes it is more convenient to leave these equations on their simple form, and to consider directly their implications on design.

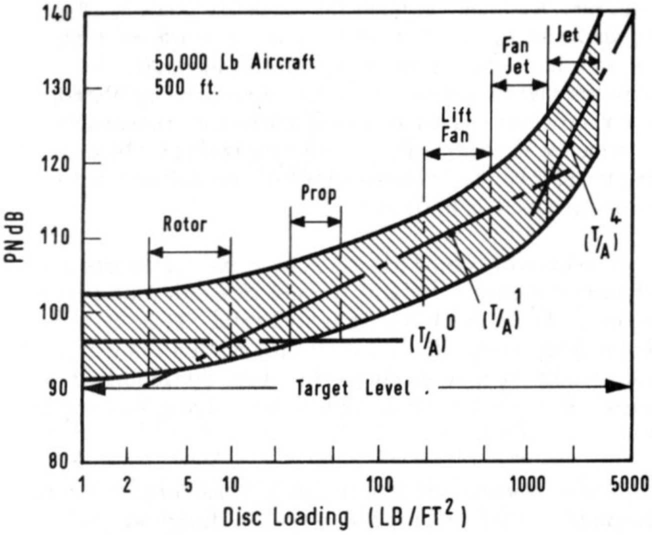


Figure 6 V/STOL Noise Levels vs Disc Loading

The basic noise trends for V/STOL aircraft are most conveniently summarized on a graph against disc loading. This was first done by Hafner(18) and subsequently several other investigators (19-23) have utilized this form of presentation. Figure 6 presents an estimate of the noise of a 50, 000 lb. thrust aircraft at a 500 ft. sideline for various forms of propulsive device. The curve is derived entirely empirically from an amalgam of the results for various forms of aircraft presented in References 18-29, and so represents estimates based on current design trends.

The key feature of the curve is the extreme disadvantage of high disc loadings for noise. Figure 6 shows how conventional jet powered air craft, characteristically operating at around 1000 lb/ft² loading produce as much as 30 dB more noise than the equivalent rotor device. New generation jet engines such as the RB211, with high bypass ratios produce less noise than conventional jets but are nevertheless penalized by their high disc loading. There are considerable advantages in a low disc loading design.

Further analysis of the basic laws governing the noise radiation shows some of the reasons for the effects shown on Figure 6. At very high loadings the jet exhaust flow is the dominant noise source. Pure jet noise obeys a U^8 law, that is a $(T/A)^4$ law, see eqn. (3), so that rapid increases in noise level at high disc loadings are inevitable. This effect is magnified still further by the increasingly higher proportion of thrust taken by the jet flow at large T/A. At lower T/A or higher bypass ratio the fan provides substantial thrust. At moderate disc loadings the noise radiation is due predominately to noise radiation from the rotating blading. Rotational noise varies as thrust times disc loading (see eqn. 1) so that for a fixed thrust sound output is proportional to $(T/A)^1$. The thrust is also a function of tip speed, varying as M^2 for constant disc loading. Thus a low disc loading low tip speed design would be optimum from the noise point of view. At the lowest disc loadings broadband radiation is the dominant source. Investigations(13, 14, 15) have generally shown that this is proportional to blade loading rather than disc loadings, at least for moderate blade loadings, as shown in eqn. 2. Broadband noise is at its most significant in the helicopter range of disc loadings. It appears that broadband noise measurements on helicopter rotors can usually be extrapolated with reasonable confidence to other forms of rotating blading. Indeed the basic formula of Hubbard(13) for propeller "vortex" noise is based on helicopter data.

The overall trends predicted by these arguments are shown on Figure 6. It will be seen that this does agree reasonably well with the empirical data. Thus the dominant noise source from a lift or propulsion system is a function of the disc loading. The noise reduction measures adopted must therefore also be a strong function of the disc loading.

These fundamental trends can be considered further. Normally, a lift or propulsion system design will be aimed at producing a fixed level of thrust T. Rotor tip velocity and blade area S will be fixed by an equation of the form

$$T = \tfrac{1}{2} \rho V_T^2 S C_T \tag{4}$$

where C_T is a thrust coefficient based on the tip velocity. For low thrust rotors $C_T \approx C_L/3$ where C_L is the blade lift coefficient. Using this, the equations (1) to (3) can be rewritten as

$$p_D^2 \sim \frac{T^3}{ASC_T} \frac{f'_D}{r^2} \tag{5}$$

$$p_B^2 \sim \frac{T^3}{S^2 C_T} \frac{f'_B}{r^2} \tag{6}$$

$$p_J^2 \sim \frac{T^4}{A^3} \frac{f'_J}{r^2} \tag{7}$$

The jet equation (7) has been found using $T = \rho \quad U^2 A$, and in equations (5), (6) and (7) the f' factors have been adjusted to include the less important variables.

All the equations show how important it is to adopt the largest possible disc area and blade area. The fundamental effect of this is to allow design velocity to be reduced. There will also be a further effect of large blade chord. W. R. Sears(30) showed theoretically that unsteady aerodynamic fluctuations tended to cancel over the chord. Thus large chord blades reduce the actual level of fluctuating forces acting, the mean square level varying as inverse chord.

The equations do miss out one vital parameter. This is frequency. It is well known that sound at very high or low frequencies is more difficult to hear, while sound in a band between 2000-5000 Hz is subjectively the most loud. Thus the frequency of the sound radiated is of fundamental importance in determining annoyance. A simple means of accounting for these subjective effects is by a frequency weighting network, and two weighting functions often used are the "A" and "D" scales previously shown in Figure 1. For the present purposes their most interesting feature is their rapid fall off, roughly as frequency squared at the lower frequencies. For low disc loading rotors the sound radiated is predominantly low frequency, so that this approximate frequency squared law will apply. This has several interesting implications.

For instance an increase in rotor size at constant thrust has a fourth power improvement on the physical levels of both the discrete and broad band noise, through the area terms on the bottom of equations (5) and (6). But furthermore, increase in size allows a proportional decrease in velocity, leading to a square law reduction in frequency. Thus, a rotor producing low frequency noise will see roughly an eighth power advantage in subjective noise level by increasing scale at constant thrust. This can clearly be turned to the designers advantage.

Next suppose the scale of the rotor is increased, but now at constant disc loading. Then thrust increases as scale squared. But frequency will reduce proportionate to the scale so that the subjective effectiveness reduces by a factor of scale squared. The net effect, therefore, is zero. Thus large or small scale models of low disc loading rotors will have essentially equal PNdB values. Alternatively it can be seen that change of thrust for constant velocity and disc loading has little acoustic effect.

The effect of number of engines is also of interest. For constant total thrust, disc loading, and velocity the choice of N engines results in each engine having N^{-1} thrust and being $N^{-\frac{1}{2}}$ in size. Since noise is proportional to thrust the physical mean square pressure from all N engines is the same as for the individual engines. But because the reduction in scale increased the frequency the PNdB value will be worse by a factor $N^{\frac{1}{2}}$. Thus, for large rotor craft producing low frequency noise there seems to be a subjective advantage in minimising the number of rotors used.

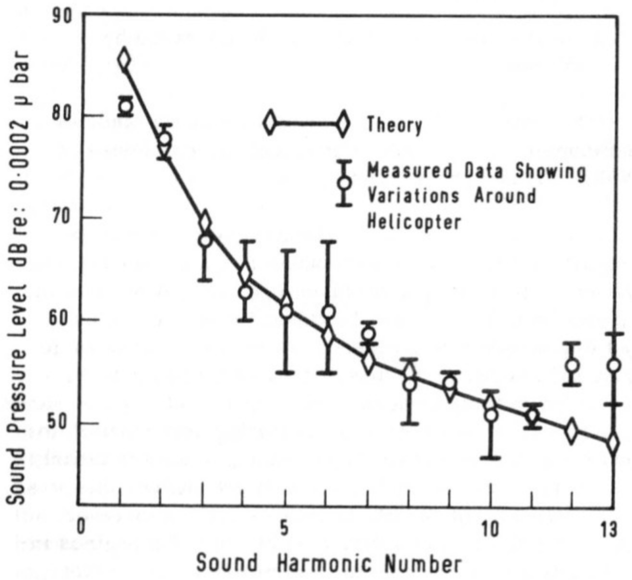
Note particularly however that these subjective arguments only apply to large rotors producing low frequency noise. As shown in Figure 1, in the mid frequency range there is little systematic effect of frequency change, while at high frequencies increase in frequency is actually desirable subjectively. This can also be of particular advantage in obtaining increased atmospheric attenuation, as was discussed in the last section.

IV. Mechanisms of V/STOL Noise Radiation

More detailed analysis of noise control methods for V/STOL aircraft requires an understanding of the basic mechanisms underlying the noise radiation. The previous section showed how rotor noise dominated the V/STOL range of disc loadings. Rotor noise subdivides into discrete and broad band components, which must be considered separately.

Discrete frequency noise radiation results from the interaction of the rotor with a non uniform input flow field, and theory exists$^{(10, 11, 12)}$ describing this noise field in terms of rotor variables. The theory regards the rotor simply as a device for converting non uniform inflow into acoustic output and shows, for instance, that the level of the tenth harmonic of a four bladed rotor of rotational Mach number 0.5 is governed by a weighted sum of the levels of circumferential distortion in all input harmonics from the 20th to 60th. Thus if the non uniform inflow can be defined, the theory gives the resulting noise radiation. It is important to note that the steady forces on the blades are of comparatively minor significance for noise (except at supersonic or high subsonic speeds).

TWO BLADED MAIN ROTOR



TWO BLADED TAIL ROTOR

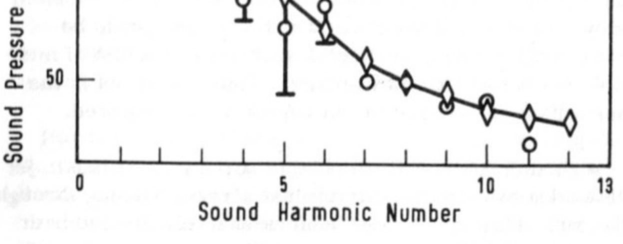


Figure 7 Theory and Experiment for Noise of a Light Helicopter (from Ref. 31.)

Unfortunately the definition of the non uniform inflow to a rotor is not straightforward, and noise predictions have relied on essentially empirical estimates of this. However theoretical predictions have had reasonable success as shown by Figure 7, taken from Ref. 31, comparing experiment with prior theoretical predictions for a light helicopter.

Recently work has been in progress at Loughborough University of Technology on a more direct proof of the theory. A small low speed fan, parameters given in Table 4, was set in an anechoic room. A rotating hot wire was mounted on the fan for direct measurement of fluctuating aerodynamic input. Acoustic output was measured via a microphone on the fan axis. This location is particularly convenient theoretically since it gives a one to one correlation between harmonics of input and output. By subtracting measured levels of aerodynamic input from measured levels of acoustic output the aeroacoustic transfer function of the fan could be obtained, as shown in Figure 8. The fan was run under two conditions; before circulation buildup, and with full recirculation in the room. As shown the aeroacoustic transfer function of the fan was similar for the two conditions, as predicted. Furthermore it agreed with theory thus providing a direct verification for the discrete frequency part of the rotor noise.

This direct relation of noise to inflow distortions is very important for the designer, since it demonstrates the necessity for careful attention to aerodynamic design to minimise any possibilty of unsteady or distorted inflow to the rotor. Clearly this must be achieved at an early stage in design layout.

Number of Blades = 2, 7 or 14

Hub Diameter = 0.24m

Rotor Disc Diameter = 0.66m

Blade chord at tip = 0.064m

Blade chord at root = 0.085m

Maximum blade thickness at tip = 0.0033m

Blade tip angles = 5°, 10°, 15°, 20°

Blade root angles = 25°, 30°, 35°, 40°

Speed range between 0 & 3000 rpm approx.

D.C. motor of 7.5 kw

½" B&K Microphone position - variable on 2.14m radius from fan centre

TABLE 4. Rig Parameters

Definition of the broadband part of the rotor noise spectrum is not straightforward. Detailed examination of helicopter noise spectra$^{(10)}$ shows that much of the noise assumed to be broad band in older work is actually due to higher harmonics of the blade passing frequency. These harmonics become wider and wider, and finally cannot be distinguished from the underlying broadband noise. Thus many of the existing empirical formulae for broad band noise include a substantial, but undefined, contribution from discrete frequency sources. Empirical definition of the relative levels of these two sources would be a valuable contribution to present knowledge, but is yet unavailable.

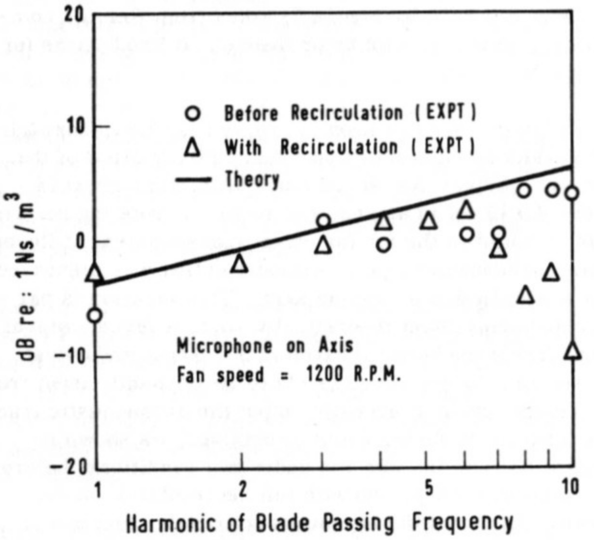


Figure 8 Theory and experiment for the rotor aero-acoustic transfer function.

Older work tacitly, or even explicitly, assumed that the broadband noise was due to a trailing edge vortex mechanism akin to the Aeolian tones arising from the Karman vortex street around a circular cylinder. The significance of this mechanism now appears to be very small(12). Rotor broadband noise mechanisms can now be seen to be due to the direct action of turbulence on the rotor. This turbulence may either be externally induced, or due to an interaction of the rotor on itself. The significance of input turbulence has been verified experimentally by Sharland(32). Estimates were also made during the recent experiments at Loughborough University of Technology(12). Measurements were taken of input turbulence using the rotating hot wire, and of radiated noise with the on-axis microphone. Discrete frequency peaks were subtracted from the spectrum allowing comparison of the underlying broadband level of both input and output. Theory was verified to better than 1 dB by this study.

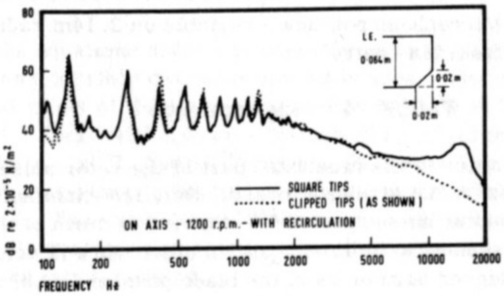


Figure 9 Effect of tip shape on noise

However the experiments also showed how the broadband sound intensity at high frequencies was, in some cases, unaffected by turbulent inflow. It was found that the high frequency rotor noise was dominated by a self-interactive source. This source of noise could be controlled via tip modifications. This is shown on Figure 9. Clipping the tip trailing edge reduces the noise at high frequency by over 10 dB. This self noise source is apparently associated with the fluctuating pressures beneath the blade tip vortex, which commences at the front of the tip.

Thus it can be concluded that rotor noise has three main components.

Discrete frequency noise, governed by inflow distortions

Low frequency broadband noise, governed by inflow turbulence

High frequency broadband noise, governed by the tips

The general conclusions should certainly apply to helicopter rotors, propellers, and various forms of VTOL lift and cruise fans.

In general terms the conclusions also apply to jet engine systems. Jet engine noise has a substantial component due to its rotating machinery, and this noise includes both discrete and broadband rotor components. Jet engine discrete frequency noise is due to the same general effects as discussed above for open rotors. However in the jet engine case inlet or outlet guide vanes can result in high levels of fluctuating aerodynamic input being imposed directly on blading. This is clearly undesirable acoustically. In early jet engines this was not realised and considerable levels of compressor noise resulted. In modern high by-pass fan engines inlet guide vanes are generally eliminated, and outlet guide vanes are positioned many chord lengths away from the rotor, minimising interaction effects. It appears that most of the discrete frequency noise from a modern design of subsonic fan engine will arise due to essentially the same mechanisms as discussed for the helicopter rotor. There is evidence suggesting that the inlet duct boundary layer can impose undesirable inflow on the rotor, but further research into the mechanics of this source is required.

Broadband noise radiation by the engine blading also occurs. As in the helicopter case empirical information on its levels exists such as that of Smith and House(33). But recent studies, for instance Mather et al(34) tend to show that much of the noise which was thought to be broadband is found on careful analysis to consist of multiple discrete frequency spikes. Thus, again as in the helicopter case, care in interpretation is required.

A further source of propulsion noise is the classic jet noise due to the turbulent exhaust stream passing through the air. This source has been extensively studied both theoretically(16) and experimentally. The recent work of Bushell(17) shows that, at low exhaust speeds, (below M=1) most of the noise is generated from internal engine sources such as the turbine and combustion chamber. Any jet engines designed for V/STOL will undoubtedly be of low exhaust speed, simply because of noise, so that conventional jet noise problems can probably be largely ignored in the present context.

An associated source is that from combined lift and propulsion systems which involve deflecting the jet stream. Noise levels due to the interaction between a solid body and a jet exhaust tend to be high, so that considerable care must be taken in the design of such a system. Further information on this may be found in References 35 - 37

No consideration has been made of possible effects of supersonic rotor operation. Intolerable radiation levels occur for supersonic propellers, or for locally supersonic action as in the high speed forward flight of a helicopter of high rotor tip speed. For rotors within a duct a further mechanism comes into play, that of non linear acoustic attenuation (38, 39). This results in the characteristic rasping noise usually known as "buzz-saw". This is typical of all present generation high by-pass engines. As will be discussed later, utilization of engine attenuating treatments can bring noise to acceptable levels even for these supersonic fans, so that the possibility of using supersonic ducted rotors, but retaining low noise radiation must not be overlooked.

V. V/STOL Noise Control

Control of noise by fundamental design parameter changes was discussed in Section 3. It will be recalled that maximizing blade and disc area gave minimum noise, largely due to the reduction of rotor velocity that this allowed for a given thrust. Furthermore Figure 6 showed how the principal noise source changed from broadband at the lowest disc loadings to discrete at intermediate disc loadings, and finally to jet noise at the highest disc loadings. Over the major region of interest therefore, discrete frequency noise is the dominant rotor noise source, and attention will be concentrated on this.

Discrete frequency noise has been demonstrated, both theoretically and experimentally, to be a direct function of the distorted inflow into the rotor. Clearly therefore, the major design goal for minimum noise is to minimize distortions entering the rotor. For a propeller the minimum, unavoidable, distortion is due to the non uniform atmosphere, but this level of nonuniformity is rather small. Distortion will also be induced by interaction with other parts of the aircraft structure. Thus low noise propellers must be positioned well clear of the wing and fuselage and also well clear of each other. These design requirements do result in performance and weight penalties, but it is probably necessary to accept these in order to design an aircraft which is allowed to operate.

For helicopter rotors the distortions may be largely due to self interaction with the trailing vortex system. Reduction of this self induced noise appears to depend on improved understanding of rotor vortex aerodynamics. However it is clear, in general terms at least, that increase of disc loading should increase downwash velocity, and thereby reduce the likelihood of blade vortex interactions. Thus in this case the improvement of the inflow conditions requires changes in the opposite sense to those based on the more general considerations of section 2. Determination of the optimum condition requires further study.

For helicopters in general it is often found that it is the tail rotor which is the dominant noise source subjectively. The tail rotor operates in a highly distorted flow field, due to both the proximity of the tail boom, and the main rotor downwash. Design modifications to remove the tail rotor from these causes of non uniform inflow seem to be comparatively straightforward, and would prove beneficial for noise.

Many V/STOL aircraft may be adversely affected by recirculation effects. Some experiments have been performed at Loughborough University of Technology to quantify the effects of recirculation on noise. These used the fan of Table 4 mounted in an anechoic chamber. A ground plane approximately 4 fan diameters square was brought progressively closer to the fan and sound measured at 40° to the axis for fan speeds from 1000-2400 r.p.m. Two fans with blade tip angles of 5° and 15° respectively were tested. The effect of change of ground plane position was consistent at all speeds, generally to within 1 dB, and average results over the eight speeds tested are plotted on Figure 10. These results are given relative to the no recirculation case, measured at the start of the fan run as described earlier in this paper.

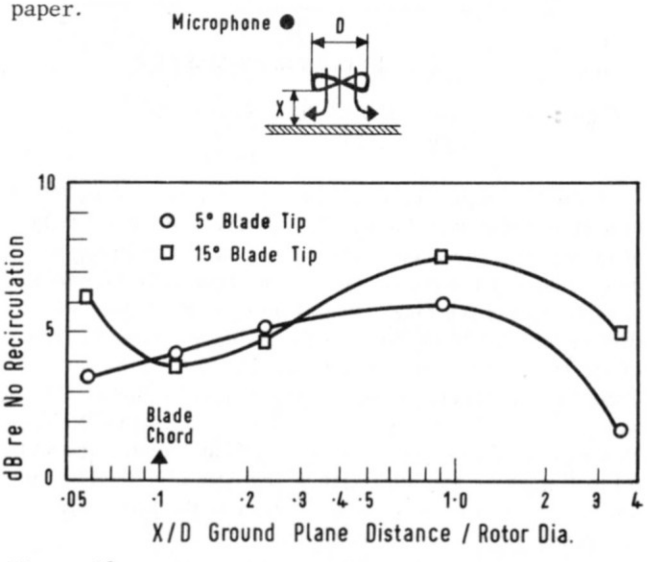


Figure 10. Effect of Ground Plane Proximity on Rotor Noise.

The results show that sound levels increase by up to 7.5 dB as the fan approaches the ground plane, as expected, down to a distance of about 1 dia. However, as the fan comes still nearer the ground plane noise levels actually reduce. Flow visualization has suggested a reason for this effect. Recirculation is apparently assisted by the ground, as expected, for moderate fan/ground plane separations. But as the fan approaches very close to the ground the flow pattern behind the fan takes the form of a radial wall jet, so that recirculation is actually reduced. Spectral analysis shows that the discrete frequency components of the fan noise are substantially reduced under these conditions, but broad band noise, if anything, increases. At the very lowest clearances the 15° tip fan shows an increase in level. This is again a consistent effect over all speeds tested. The reason for this is not known in detail, but it is thought that it corresponds to the blades coming within 1 chord of the ground plane so that a direct blade/ground interaction dominates.

The strongest ground recirculation effect (7.5 dB) was found for the more highly loaded fan tested. This is probably more representative of V/STOL cases. The experiments also suggest that the effect is slightly stronger at the highest velocities. Since the present experiments were carried out a maximum tip Mach number of 0.24, further study at higher tip Mach numbers is suggested.

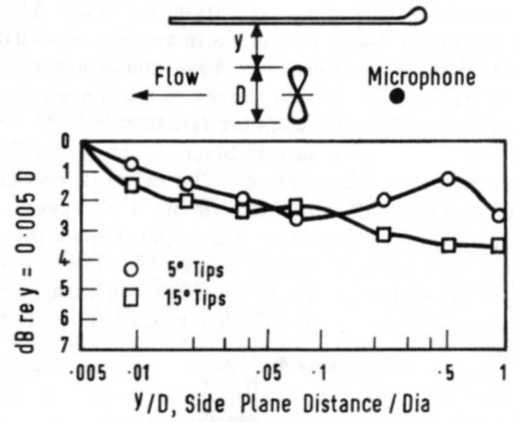


Figure 11. Effect of Side Plane Proximity on Rotor Noise.

A further experiment has been performed on the effect of a side plane simulating, for instance, the proximity of an aircraft fuselage. The same board was brought progressively nearer to the fan, but now with the board parallel to the fan axis. Preliminary studies showed that separation from the side plane leading edge in front of the fan could cause marked increases in noise level. Thus for the present experiments a smooth plastic fairing was added to the board leading edge. As before the fan was run over a range of speeds, and the results presented in Figure 11 are averages of the data taken. The results are given relative to the levels at the minimum fan/plane separation of 0.005 D.

The results for this experiment are less clear cut. The maximum change in noise level observed was just over 3 dB. Furthermore there is no immediately obvious explanation for the secondary noise peak for the 5° tip blades at about 0.5 dia. separation. Possibly the effects were masked by the general level of recirculating flow within the anechoic chamber, but if any substantial effect was present it would presumably have been recorded. Therefore it is tentatively concluded that rotor side plane interactions are of comparatively minor significance. From the design point of view this indicates that propellers can be located reasonably close to the fuselage without severe noise penalties. The criterion must be to keep the propeller disc outside any possible region of local separated flow on the fuselage. The critical condition for this will be the maximum yaw case.

Older designs for V/STOL aircraft often featured fan in wing and similar designs. It is quite clear that such fans must operate in severely distorted and possibly even separated flow, especially during transition. Typical disc loadings for these designs were in the 200-500 lb/ft class so that noise levels would be expected to be unacceptably high. It appears that such designs suffer from sufficient noise disadvantages to preclude their further consideration.

However use of specially designed jet engine lift fan devices is a different problem. It may be possible to tilt these for optimum conditions. A more important advantage is the existence of a duct. This can be used to mount acoustic lining materials. Lining technology has now progressed to the point where virtually any desired noise attenuation can be achieved, especially if the engine sound field is designed to be optimum for in-duct attenuation. Possibly transonic rotors with good mechanical performance will be acceptable in an attenuated duct configuration. Performance penalties for linings in a pure lift engine are likely to be acceptable because the engine only operates for a proportion of the time. Weight penalties may be more significant, but it should be possible to dispense with the inlet linings for a lift engine since the inlet sound is radiated upwards. Furthermore, a small lift engine could be designed with large blade numbers so that it is a high frequency source with all the attendant community noise advantages discussed in Section 2.

For very low disc loadings Figure 6 shows how the rotor noise field will be predominantly due to broad band radiation. The experiments reported earlier herein showed that the broad band noise was due to two sources, input turbulence governing the low frequency end, and tip effects governing the higher frequency. The split between these two for the present experiments was at a Strouhal number of around $fc/U=4$. Control of the low frequency broad band noise levels is simply a question of reducing turbulent input levels. This can be achieved by virtually the same measures as discussed for the discrete frequency case where distorted input had to be minimised. For turbulent flow frequencies tend to be rather higher, and wavelengths smaller, so that advantage can be taken of Sears(30) effect of reduced response as wavelength reduces compared to chord. A limitation to this will be imposed by direct quadrupole radiation when $fc/a_o \gg 1$ (a_o is the speed of sound), but over a useful range each doubling of chord will correspond to a 3 dB decrease in noise radiation. This effect will also apply to the levels of the higher harmonics of the discrete frequency noise.

At the higher frequencies the tip noise source may be dominant. For large and/or low speed rotors the tip noise frequencies may lie in the region of maximum subjective response. Indeed data(40) for conventional helicopters suggest that just such a peak may occur at around 2000 Hz. Figure 9 showed that modifications to the blade tips can be a remarkably effective control measure for higher frequency noise. Systematic tests(12) show that such tip sources only exist over a limited range of tip operating conditions, so that change of tip incidence may be equally effective.

Noise benefits due to tip modifications have been reported by many workers, for example in References 41-43. Benefits have been claimed over the whole spectrum of rotor noise radiation. Other workers have had difficulty reproducing these results, indeed Leverton(28) found a consistent increase in noise radiation for all tip modifications. In the midst of these uncertainties the one clear conclusion is that tip shape can have a significant effect on noise. Thus tip shape studies would appear to be a valuable addition to any rotor noise control program.

Simulated "owl wing" leading edges have also been shown to reduce noise radiation. The wing is modified by the addition of multiple miniature strakes extended forward of the leading edge. Hickey(43) presents figures showing a 5-10 dB reduction at the higher frequencies for a model propeller. In the author's opinion,the most likely cause of the benefit is the suppression of unsteady laminar separation phenomena on the top surface of the wing. Thus,it is not expected that the effect would be duplicated on full scale rotors. Nevertheless, some further study is justified.

The effect of blade number is rather interesting. Theory(10) for the discrete noise radiation shows that increasing blade number results in an increased cancellation of harmonics, and so is entirely beneficial. Thus over the disc loading or tip velocity range where discrete frequency noise dominates minimum noise requires large blade numbers. But broad band noise radiation is affected in an opposite manner. Increase of blade number causes a reduction in chord and an increase in the natural frequency of the sound radiated, which brings it into the more subjectively annoying range. Thus for low disc loadings and low tip speeds a minimum blade number is indicated. Furthermore an additional benefit of increased chord is to reduce noise by the Sears(30) effect discussed earlier.

Low Disc loadings (T/A $<$ 20 Lb/ft^2)	High Disc loadings (T/A $>$ 200 Lb/ft^2)
Minimize aerodynamic interactions	Use duct treatments
Minimize tip velocity	Minimize aerodynamic interactions
Maximize blade area	Increase number of blades
Optimize tip shape	Minimize tip velocity
Reduce number of blades	Maximize disc area.

TABLE 5 Summary of Methods for Rotor Noise Control

VI. Conclusions

Table 5 above summarises noise control measures which can be adopted for high and low disc loading rotors, designed to current practice. In each case the recommendations are given in rough order of priority. Once these major design parameters are chosen, acoustic effects of detail design modifications tend to be small. Note that the high disc loading case of Table 5 does not include transonic rotors which are somewhat outside the scope of this paper.

Acceptable V/STOL aircraft operation from the noise viewpoint is likely to require noise levels of less than 90 PNdB at the airport boundary. At the present time the only form of aircraft likely to meet this is a low disc loading helicopter. The proposed Sikorsky S-65-200 compound helicopter is estimated(22) to produce 93 PNdB at 500 ft. Equivalent STOL aircraft are measured(44) at over 110 PNdB at 500 ft. Sufficient is not known about the detail mechanisms of rotor noise radiation to allow the 90 PNdB figure to be achieved with some design readjustment for the lower disc loading ranges (say T/A $<$ 20 lb/ft^2). At higher disc loadings reduction of open rotor noise to an acceptable level will be difficult, and this probably precludes the use of such rotors in urban transportation. Ducted rotors allow incorporation of attenuating treatments, which can give major reductions in noise output. Present designs for ducted engines suggest(26) that 95 PNdB at 500 ft. should be attainable.

For future lower noise V/STOL aircraft two approaches are possible. Either a low disc loading rotor or a direct lift engine could be feasible. Achievement of acoustic target levels will involve penalties in either case, due to increased size and weight for the rotor, and to the performance and weight penalties of the acoustic treatment for the lift engine. Successful development of a low disc loading rotor also requires considerable improvements in knowledge of rotor aerodynamics, and in structural design methods for large rotors. However, conventional engine technology should already be able to meet the requirements of the high disc loading design case. Furthermore, this offers the additional possibility of design for high frequency noise, with attendant major reductions in overall community annoyance.

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