Comparison of Broadband Noise Mechanisms, Analyses, and Experiments on Rotors

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A study is made of the various mechanisms which generate broadband noise on a range of rotors The sources considered are load fluctuations due to inflow turbulence, due to turbulent boundary layers passing the blades' trailing edges, and due to tip vortex formation Vortex shedding noises due to laminar boundary layers and blunt trailing edges are not considered as they can be prevented in most cases Various prediction methods have been reviewed and extended in some cases An extensive search was made of existing experiments and calculations based on the various prediction methods were made This study shows that present analyses are adequate to predict the spectra from a wide variety of experiments on fans, full scale and model-scale helicopter rotors, wind turbines, and propellers to within about 5 to 10 dB Better knowledge of the inflow turbulence improves the accuracy of the predictions The results of this study indicate that inflow turbulence noise depends strongly on ambient conditions and dominates at low frequencies Trailing edge noise and tip vortex noise are important at higher frequencies if inflow turbulence is weak Boundary layer trailing edge noise is important especially in the presence of large rotors; it increases slowly with angle of attack but not as rapidly as tip vortex noise, which can be important at high angles of attack for wide chord, square edge tips

Introduction

IN spite of intensive research over the past 50 years and particularly over the last 15 years, the relative importance of various rotor noise mechanisms is only partly understood. The accuracies of the existing analyses are also hard to document. The primary reason for these difficulties is that there are a large number of noise mechanisms on rotors which can be important in different parts of the acoustic frequency spectrum, depending on the rotor parameters and operating environment The wide variety of source mechanisms is due to various aeroacoustic effects: boundary layers, separated flow, and inflow turbulence; high Mach numbers, including nonlinear effects; blade vortex interactions; nonuniform inflow; etc.[1] In general, each of the mechanisms affects different parts of the acoustic spectrum Then, on craft with either tandem or main and tail rotors, many of these mechanisms can interact with each other and between rotors Thus, in many cases, it has not been clear which mechanisms are dominant in many operating conditions for full scale helicopters, wind turbines, etc. This study addresses the broadband noise part of the problem It will review broad band noise mechanisms and compare calculations, based on various researchers' analyses of broadband noise mechanisms, to each other and to available experimental data The aims of this work are to help understand which broadband noise mechanisms are important in which cir cumstances, to identify a number of satisfactory, existing, and well-documented experimental measurements, and to evaluate the various analytical approaches by comparing them to each other and to the chosen experiments It will be seen that several satisfactory analytical approaches are available They can show which mechanisms are important in which cases and are able to predict absolute spectra to within about 5 dB for clean experiments

The frequencies of interest in rotor noise are usually determined by human annoyance (or detection in some cases) The common measures of annoyance, such as the perceived noise level (PNdB) or A weighted sound level (dBA) account for the fact that humans find low frequencies, say, below a few hundred Hz, much less annoying On the other hand, if long distance propagation is a factor for the rotor in question, then high frequencies can be attenuated significantly by molecular absorption.[1] Thus, frequencies ranging from a few hundred to several thousand Hz are of primary interest.

The amount of power radiated by a rotor is generally ex tremely small, compared to the aerodynamic power consumed by the rotor (by a factor of order of 10^5 or more) Thus, the acoustics do not affect the rotor performance to any extent Noise is radiated by forces, volume displacements, or nonlinearities which are either unsteady or vary in their effects when considered in terms of retarded time [1] In general, rotor noise can be divided into three categories

1) Discrete frequency noise (sometimes called rotational or harmonic noise) is caused by steady or harmonically varying forces, volume displacements, or nonlinear flow effects For low to moderate blade tip Mach numbers, these can be due to the basic blade rotation and forward flight of a helicopter or to steady inflow variations These mechanisms have been analyzed by Gutin, Deming, Hubbard, Lowson, and Wright The steady loading noise is generally restricted to the first dozen or so harmonics of the blade passing frequency and thus is not usually of importance to helicopter main rotors or large wind turbines since these frequencies lie in the frequency range below 100 Hz where human ears are not very sensitive These low order harmonics are, however, very important to the helicopter tail rotor cases Harmonically varying effects can, in principle, be important at higher frequencies for all rotors; but, in fact, the higher frequency noises tend to be caused by loads, displacements, or nonlinearities which are impulsive, high Mach number, or randomly varying (caused by turbulence) In these cases, the phenomena are better analyzed as impulsive or broadband noise as discussed below

2) Impulsive noise (sometimes called blade slap) consists of more or less distinct repeated pulses at blade passing fre

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quency. After being Fourier analyzed, the repeated pulses will yield discrete or harmonic spectra Their particular identity, however, is due to their impulsive time histories and origins In particular, they are caused by events at certain blade azimuth angles such as blade vortex interactions or local transonic blade motion toward the observer (say, Mach number greater than approximately 0 75) These noise sources have been analyzed by Widnall, Ffowcs Williams and Hawkings, Farassat, Hanson, and Schmitz, et al , and George and Chang [2-9] Impulsive noise is unquestionably the most important noise source on helicopter or wind turbine rotors when it exists However, a prime goal of aeroacoustic rotor design or operation is to avoid impulsive noise generation by control of blade-vortex interactions and avoiding high tip Mach number This often leaves broadband noise as the important controlling noise in many situations where relative tip speeds are not transonic and blade-vortex interactions are avoided

3) Broadband noise the subject of this study, has a continuous (although sometimes humped or peaked) spectrum and is caused by disturbances which are not precisely repeated at each blade revolution, but which are basically random in nature These random disturbances are generally due to some sort of turbulence interacting with the rotor blades The turbulence either can be incident on the blade from the ambient atmosphere or can be generated by the blade motion itself A recent review of broadband noise research may be found in Refs 10 and 11

Broadband Noise Mechanisms and Analyses

For this study, various analyses of broadband noise were programmed (and extended in some cases) Emphasis is placed on "first principles" analyses which make absolute predictions of noise spectra and do not require the determination of empirical constants for different families of rotors Computations were made for a wide variety of rotors in order to compare different analyses of the same mechanisms to each other and to available experiments This enabled us to determine which mechanisms are important for different rotor parameters and in different parts of the audible spectrum A few comparisons are also given for some of the scaling-law based correlations available in the literature.

Historically, the first broadband noise prediction methods were fundamentally based on empirical correlation of overall sound pressure level (OASPL) as for example, by Widnall [12] Previously, very early investigators had erroneously identified broadband noise with some sort of turbulent "vortex shedding" from the rear of the blades; hence the early name "vortex noise" was used Actually, most broadband noise is due to force fluctuations on the blades due to influences of turbulent flows Later, it was found that in the atypical case of laminar flow, the laminar boundary layers on blades can indeed shed nearly regular vortices at the trailing edges and thus radiate a narrow, peaked broadband sound, sometimes called "high frequency broadband noise" (See, e g , Paterson, et al ,[13] Aravamudan et al [14]) However, this source is not important on most full scale rotors, except, perhaps, on helicopter tail rotors or small fans Even then, it can be eliminated easily by tripping the boundary layers (see e g Ref 14)

According to the origin of noise produced, the source mechanisms considered in this study can be divided into the categories which follow

Inflow Turbulence Noise

The analysis of the sound generated by the unsteady loadings due to turbulence fluctuations on unducted subsonic rotors began with the quite general analysis of Homicz and George,[15] who treat the general case of unsteady forces distributed in space following the Lighthill equation of aeroacoustics with specialization to rotating blades. They devised an analysis for the sound radiated from arbitrarily varying forces on a rotor disk The analysis was then applied to the varying loadings on a rotating blade in the disk The loadings were obtained from an approximate compressible aerodynamic analysis for an inflow of isotropic turbulence defined by the Dryden spectrum Inflow turbulence was seen to be an important noise source over a range of frequencies. Also, the analysis explained the humped or peaked nature of the low frequency part of the spectrum as due to the large scale components of the turbulence inflow These large scale components give nearly periodic disturbances as they are swept through the rotor plane; this leads to nearly periodic but finite bandwidth radiated sound. This analysis is not well suited for high frequencies, since large CPU times are required for the calculations; thus, high frequency analyses were developed by George and Kim[16] and by Amiet,[17] and variations on them by Harris and coworkers [18,19]

The high-frequency analysis of George and Kim[16] approximated the distributed blade forces as rotating concentrated forces (dipoles), then used the result of Ffowcs Williams and Hawkings[20] to obtain the noise radiation The analysis assumed the force components in the observer direction are statistically stationary; this effectively restricts the analysis to the forces normal to the rotor plane and thus does not allow accounting for the much smaller torque forces which can be significant for observers near the plane of rotation, nor for the detailed radiation directionality of the blade elements The assumption of circular motion also does not allow accurate treatment of forward flight helicopter cases However, as will be seen later in this paper, these are not important restrictions except for within about 15 deg of the rotor plane or for advance ratios greater than about 0 4 (which is beyond the range of interest for typical helicopters) The analysis gives a reasonably simple equation for the radiated sound It gives some analytical insight into the noise generation mechanism's dependence on rotor parameters and it can also be evaluated numerically in a straightforward manner

The method of Amiet[17] is based on a different concept. Initially, Amiet analyzed the radiation of sound from a stationary, nonrotating airfoil in a uniform mean flow containing turbulence [21,22] This analysis accounted for the full range of wavelength to chord ratios and accurately predicted the directionality of the radiation Later, Amiet used these results to synthesize the average radiation from rotating blades by numerically summing and averaging the radiation from a series of blade straight line motions which approximate the circular (or epicycloidal) motion of a hovering rotor [17] This approach neglects the radiation due to the acoustic sources and is thus restricted to acoustic frequencies which are large compared to the rotor frequency (i e , $\omega >> \Omega$) for Mach numbers not near one. This approach can account for the part of the correlation effects due to successive blades chopping the same eddy if it is slowly convected through the rotor plane. However, it does not account for the simultaneous correlation of angularly spaced blades cutting large scale turbulent components (scale of order blade radius) The neglect of this effect also requires $\omega >> \Omega$ Thus, it and the George and Kim[16] analysis, which neglects all correlation effects, are both valid for high frequencies, with somewhat lower frequencies being allowable in Amiet's analysis Amiet's method has the advantage of being able to treat forward flight easily and being based on a more exact model of radiation directionality However, as will be seen later in this paper, when one sums and averages the multilobed radiation pattern over the range of directions to the observer, the pattern is smoothed out to a pattern which, except very near the rotor plane, is quite close to the simpler dipole pattern resulting from the approximations of George and Kim Harris and coworkers[23,24] have carried out a range of experiments on broadband noise from model rotors and, in conjunction with their work, have developed analyses based on variations of the two methods discussed above

The methods of George and Kim and of Amiet were used in the present study for inflow turbulence noise calculations. The inflow turbulence itself can be due to the natural turbulence in the atmosphere or due to upstream disturbances as in the case of a helicopter tail rotor ingesting the wake of the main rotor In making the calculations for this study, the incident turbulence properties often had to be estimated based on the average measured properties of atmospheric turbulence[25] or were roughly estimated based on energy considerations.[26] In those cases, alternative calculations were made to illustrate the sensitivity to the likely range of values. Another difficult problem in estimating the turbulent inflow properties is due to the anisotropic nature of the inflow due to the distortion of turbulent eddies as the contracting streamlines enter hovering rotors, stationary propellers or fans [1 27 28] At present, this effect also can only be estimated and alternative calculations made.

Boundary-Layer Trailing Edge Noise

Noise is also produced by the self generated turbulence in a blade's boundary layer passing its trailing edge This was recognized as far back as 1959 [29] Various investigators developed very simple models for this noise, but these early models were not complete and were basically useful as bases for correlations. Fink, for example, used such a correlation to predict the on-axis noise of a rotor due to boundary layer trailing edge noise.[30] Complete first principle analyses of rotor trailing edge noise were developed more recently by Kim and George[31] and by Schlinker and Amiet [32] Recently, Hubbard, et al [33] also have proposed an OASPL and spectrum peak correlation for wind turbine rotors

The analytical problem of sound radiating from the effect of turbulence being convected past a nonrotating trailing edge has been studied intensively since about 1970 A variety of models were studied (see the review of Howe[34]), but these primarily resulted in scaling laws which needed determination of empirical constants. There also remained a number of questions regarding the details of the modelling and the effects of the Kutta condition. On the other hand Amiet developed a method which is based on solving the problem of a statistically stationary pressure field being convected past a trailing edge [35,36] This result depends only on the pressure spectrum in the boundary layers being known from experiments. Amiet's method has been compared to the experimental findings of Brooks[37] and found to be consistent

In 1980, Kim and George constructed an analysis of boundary-layer noise from rotors by using the blade forces from Amiet's flow model in the same manner as they had earlier for the inflow turbulence noise Thus, their analysis is again restricted to angles not too close to the rotor plane and to the low advance ratios which are found in helicopter forward flight In the calculations given in this paper, an airfoil boundary layer thickness correlation was used[38] instead of the flat plate results used in the original publications It should be noted that the results from either of these analyses depend upon the accuracy of the models for the pressure spectrum convecting past the trailing edge These are not yet unequivocally established for airfoils Later, Schlinker and Amiet[32] used the same numerical summing and averaging method that Amiet had used for the inflow turbulence noise[17] to treat the trailing edge noise problem. Again, we will see that the dipole method of Kim and George gives essentially the same results as Amiet's method except within about 15 deg of the rotor plane where additional source terms should be included in both methods

Tip Vortex Noise

Another source of broadband noise on airfoils or rotors is that of locally separated flow from local stall or from tip vortex formation Kendall,[39] Ahtye et al ,[40] and Fink and Bailey[41] experimentally observed localized noise sources at wing and flap tips Changes in noise from changes in rotor tip shape were experimentally observed some time ago by Lowson et al ,[42] although these effects may have been due to blade loading changes. Also earlier, Revell,[43] for the airframe noise case, had argued on an energy basis that vortex drag and associated turbulence in the trailing vortices must lead to additional noise in some manner. George et al [44] have identified this effect with the turbulence in the vortex formation and local separation region over the blade tip interacting with the trailing edge.

The model starts from experimental observations of separation on the suction side of blade or rotor tips due to the boundary layer being swept around the tip by the pressure gradients at the tip. A separated vortex flow results which is very similar to the flow over the top surfaces of a sharp edged delta wing in subsonic flow It is known that these leading edge vortices are quite turbulent Large fluctuating pressures have been measured on the surfaces of delta wings under these vortices George et al [44 45] used these data, pressure fluctuation data from two dimensional flows, and data on the geometry and velocities associated with wing and rotor tip flows to estimate the separated turbulent pressure spectrum being convected past the trailing edge This information was then used to predict the resulting radiated sound in a manner similar to George and Kim's treatment of inflow turbulence and boundary-layer trailing edge noise This tip vortex noise is shown to increase with blade loading as had been experimentally observed in many cases The updated version of the analysis[45] uses turbulent pressure data measured under vortices on delta wings which are then correlated with rotor tips using experimentally measured length and velocity scales This version is used to complete spectra for the various cases in the present study

Other Mechanisms

Another local separation turbulence noise is that of local stall due to high angle of attack, where the angle of attack is due to close proximity to a vortex from previous blade passage This phenomenon was studied experimentally by Paterson et al.,[46] but there is presently no analytical model of either the local separation or noise radiation available However, available detailed pressure measurements on rotor blades indicate that this phenomenon usually is not present on rotors under normal operating conditions [47]

As mentioned in the Introduction, trailing edge vortex shedding noise from laminar blade boundary layers is a noise mechanism which can be eliminated in most cases by tripping the boundary layer. A similar mechanism of vortex shedding from blunt trailing edges has been identified for turbulent flows as well by Brooks and Hodgson [48] Analogously to the laminar flow case, this noise source can be eliminated by using sufficiently sharp trailing edges

Comparisons of Analyses to Experiments

As discussed in more detail in Ref 11, not very many experiments reported in the literature present "clean" spectral data, unaffected or minimally affected by extraneous influences such as reverberation, engine, or drive motor noise etc In order to find experiments suitable for comparison, we also looked for the most complete measurements available of the inflow turbulence spectrum and tried to choose representative data covering a range of rotors from wind turbines to helicopters We did not consider data where only overall sound pressure level or octave band data were given, since this type of averaged data is inadequate for differentiation between source mechanisms and analyses

In the comparisons, the data estimated as input to the analyses and to the correlations are given in the figure captions Other input parameters were taken from the experimental papers Inflow velocities were estimated using simple momentum theory with thrusts determined by simple blade element theory As will be discussed later, the inflow turbulence properties were often estimated. In many cases, we will show inflow turbulence noise calculations based on both the Von Karman and the Dryden models for the inflow turbulence spectrum

In cases where separate calculations are shown for separate mechanisms, the results should be summed to compare to the experiments It is comparatively easy to envision the sum on the decibel scale The highest of the curves essentially determines the level, with only a 3 dB increase if two additive curves have the same level and a 4 8 dB increase if three additive curves have the same level However, in order not to clutter the figures, this was not done in this paper

The cleanest full scale helicopter rotor data available are probably those of Leverton [49 50] He tested a full scale rotor on a test rig in an inverted position in order to eliminate the effect of recirculation, which occurs when the rotor wake is directed toward the ground He reported spectra measured using a tethered balloon at a range of angles to the rotor plane His tests varied both loading and rpm, although in this paper we have chosen only a few cases for comparison Unfortunately, neither the turbulent intensity nor the scale were measured As the inflow was drawn from near the ground, the integral scale could be quite reasonably estimated from the fairly well established empirical relationship of $\Lambda = 0\ 9\ h$, where Λ is the integral scale and h is the height above the ground [51] Similarly, values for turbulent intensity for various weather conditions also can be estimated from the extensive data and correlations in Lumley and Panofsky's monograph [25]

Figure 1 compares a range of predictions to one set of data from Leverton [50] These data were taken at an angle of -75 deg from the rotor plane where all the analyses would be expected to be within the range of their assumptions It is clear that the correlation of Pegg[52] is too high for this case It is also clear that at the lower frequencies, say below 1000 Hz, the boundary layer trailing edge noise and the tip vortex noise are not important At higher frequencies, say, above 1000 Hz, they become important, with boundary layer trailing edge noise being the more important one in this case. Fink's boundary-layer noise correlation is seen to be a reasonable approximation to the more exact boundary layer noise calculations Most of the noise below 1000 Hz is shown to be inflow turbulence noise based on the estimated turbulence properties Both the analyses of George and Kim[16] and that of Amiet[17] agree within about 5 dB of each other and with Leverton's data

In Fig. 2, a comparison of calculations to the data of Leverton taken at an angle of $-11\ 5$ deg from the rotor plane is shown As all these analyses ignore in-plane force com ponents and as George and Kim use a blade dipole directivity, the agreement would not be expected to be quite as good; on the other hand, it is not clear how much of the differences are due to which effects

Figure 3 shows a comparison for a full-scale wind turbine. The data were measured by Shepherd and Hubbard for the MOD OA wind turbine at ground level and a distance of 61 m from the tower base [53] The agreement with the predicted absolute spectra is excellent using estimated turbulent properties, and it is seen that the primary source for frequencies above about 1000 Hz is boundary-layer trailing-edge noise as was also suggested by Hubbard and coworkers [33 53]

Indoor tests of model rotors in anechoic facilities are also available for comparisons to analyses The set presented here was carried out by Paterson and Amiet in the UTRC anechoic wind tunnel facility on several model rotors [54] In these tests, both vertical ascent and forward flight were simulated, and different grids were used upstream to generate controlled inflow turbulence Measurements were made for both the turbulent intensity and scale so that in these cases none of the parameters needed for input to the analyses needed to be

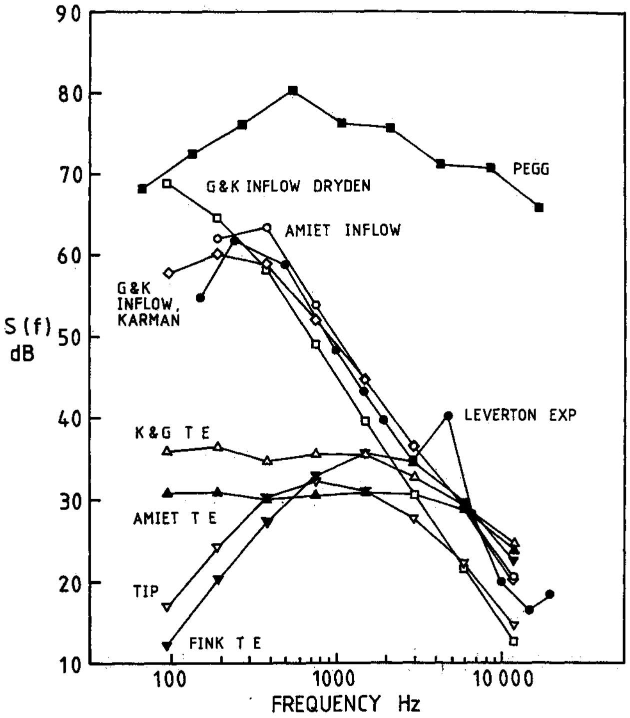

Fig 1 Comparison of the range of predictions for a full-sized helicopter rotor with experiment of Leverton;[50] $\phi = -75$ deg, $\Lambda = 0\ 57$ m, $\sqrt{w^2} = 1$ m/s

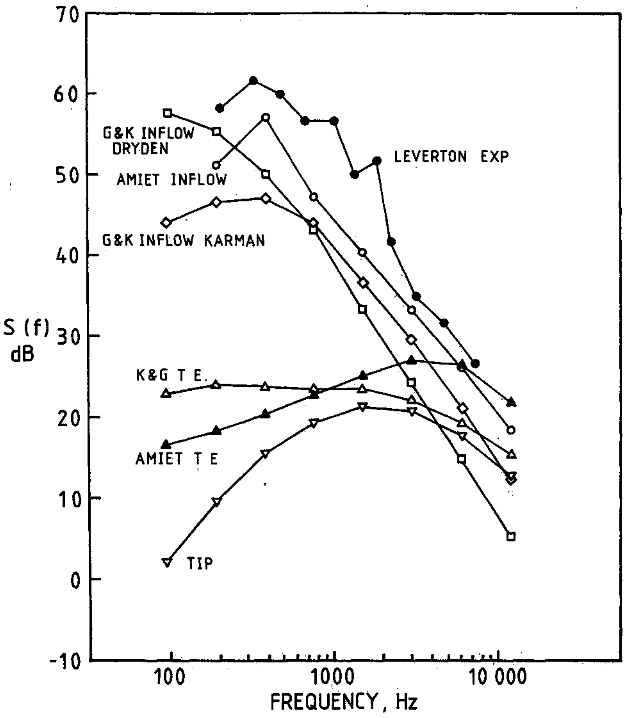

Fig 2 Comparison of predictions with the experiment of Lever ton;[50] $\phi = -11.5$ deg; same turbulence properties as in Fig 1.

estimated Figure 4 shows comparisons of calculations to the no grid (low inflow turbulence) case It is clear that both tip and boundary layer noise are important at the higher frequencies Figure 5 shows the case where an upstream grid was used; inflow turbulence noise became the primary noise source, as was also predicted by Paterson and Amiet All cases we have calculated agree to within about 5 dB of the experiments In their report, Paterson and Amiet have also shown good agreement using Amiet's inflow turbulence analysis whenever the primary noise noise source was inflow turbulence noise

The final set of data we will use for comparison is that of Lowson et al.[42] for a low speed fan Tests were run in an anechoic room, with both ducted and unducted fans and both before and after recirculation built up in the room The nonrecirculation conditions were better defined and were used for our comparison The experiments had varying rpm, tip pitch angle, and tip shape The turbulence was measured by a limited frequency range hot wire, which gave reasonable estimates for the turbulent intensity in the room before recirculation set in. We estimated the turbulent integral scale to be 0 1 m The boundary layer was not tripped in these tests, thus leading to some laminar vortex shedding humps in the high-frequency part of the spectrum which we ignored (It is interesting to note that when the tip was cut back in the tests, the laminar boundary layer hump was greatly reduced) Figure 6 compares some of the data to correlations and calculations Again the correlation of Pegg[52] seems to be too high. Here the inflow turbulence noise is predicted to be important over the full range of frequencies and the calculations agree very well Similar excellent agreement was found for cases with different rpm or different tip pitch angles

Comparisons of Analyses to Each Other

In this section, the results calculated by the methods of Amiet and of George and coworkers are compared to show the effects of different assumptions in the analyses The computational approach of Amiet allows treatment of forward flight (nonzero advance ratios), and more accurate basic blade noise directionality The George and Kim approach has been implemented for both the Von Karman model and the Dryden model of the inflow turbulence spectrum We will examine each of these effects by comparing the results of the calculations made by different methods

Figure 7 gives the plots of the Dryden spectrum, which is available in the George and Kim inflow turbulence model, and of the Karman spectrum, which is available in both the George and Kim and Amiet models It is clear that the Karman spectrum contains more energy at high frequencies Although the Doppler shifts complicate things, one can roughly identify a given frequency radiation with the inverse time for a blade to pass through a turbulence component of length $1/k$, where k is the wave number Referring to Fig 7, we see that the difference between the two atmospheric turbulence models can be of order 10 dB at these wave numbers Figure 8 shows comparisons between inflow turbulence noise calculations for a full scale rotor for both 0 1

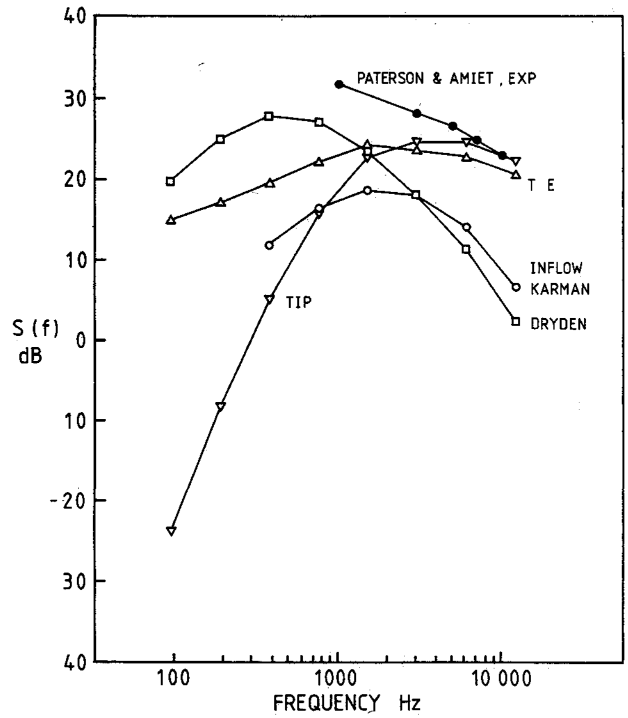

Fig 4 Comparison of predictions for model rotor, experiment of Paterson and Amiet,[54] no grid, TEST VA C 1

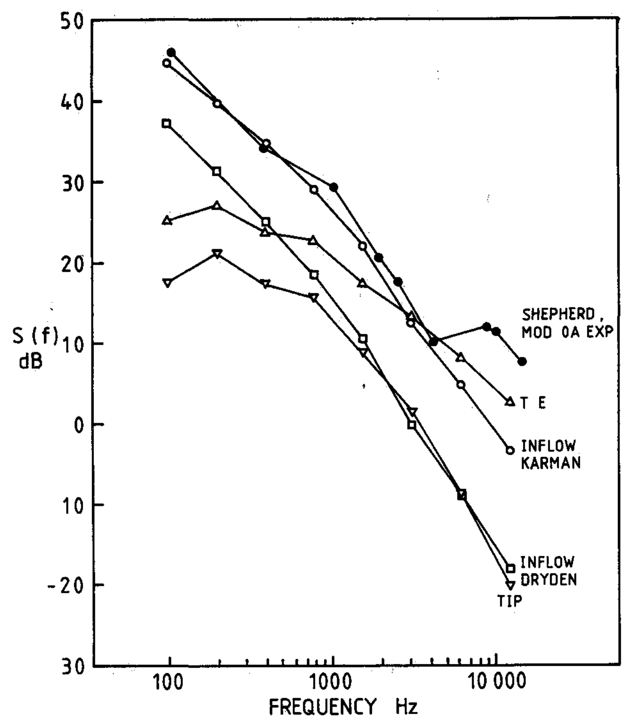

Fig 3 Comparison of predictions with Shepherd and Hubbard's experiment[53] for MOD OA wind turbine; $\Lambda = 27\ 5$ m, $\sqrt{w^2} = 1$ m/s

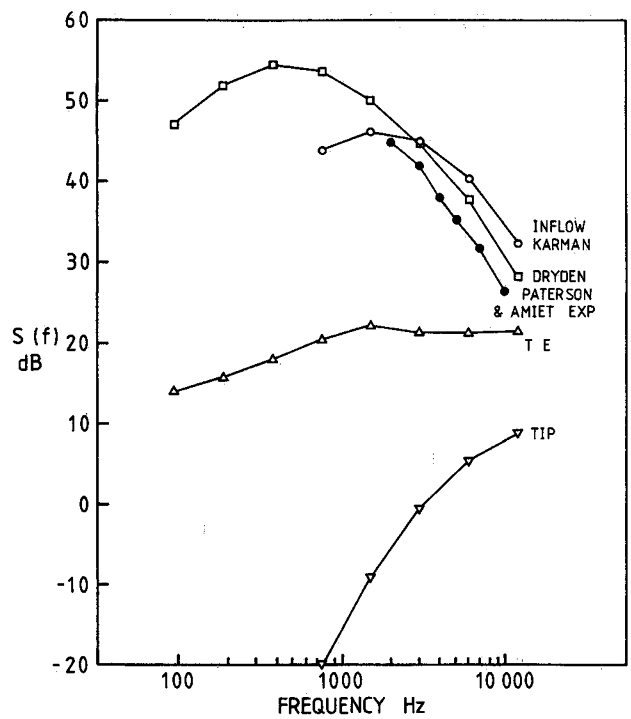

Fig 5 Comparison of predictions for model rotor, experiment of Paterson and Amiet,[54] medium grid, TEST VA M 4

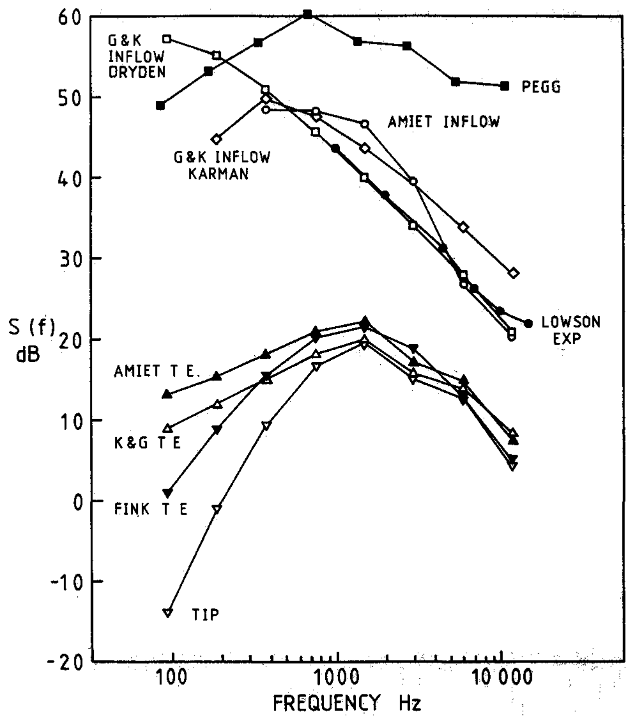

Fig 6 Comparison of predictions for low speed fan noise, experiment of Lowson,[42] 1500 rpm, tip pitch = 15 deg

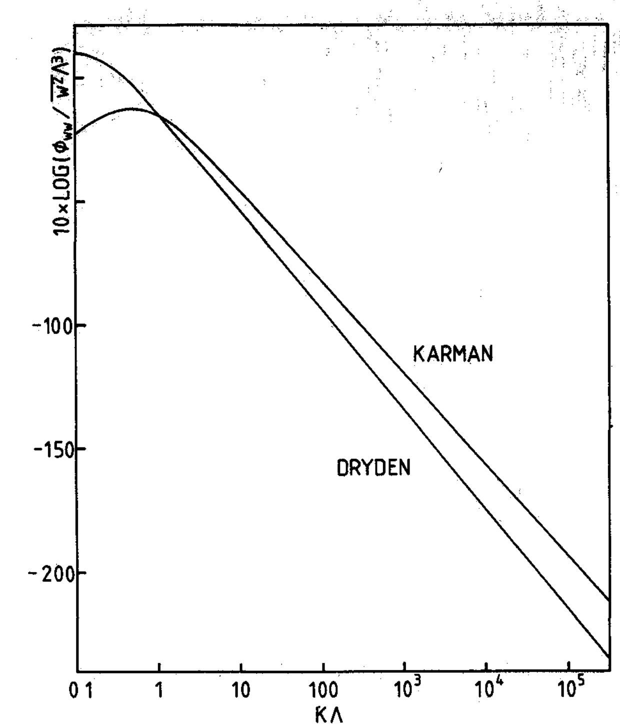

Fig 7 Comparison of Von Karman spectrum and Dryden spectrum models of atmospheric turbulence

and 67 0 m integral scales It is apparent that for a small integral scale and low frequencies, the results for different assumed turbulence spectra are in close agreement although even then, the differences become more marked at high frequencies One concludes that the Von Karman spectra should be used particularly for cases where the integral scale is large However, some comparisons in the previous section indicated that for indoor tests in which small scale turbulence is involved, the Dryden spectrum gives better results.

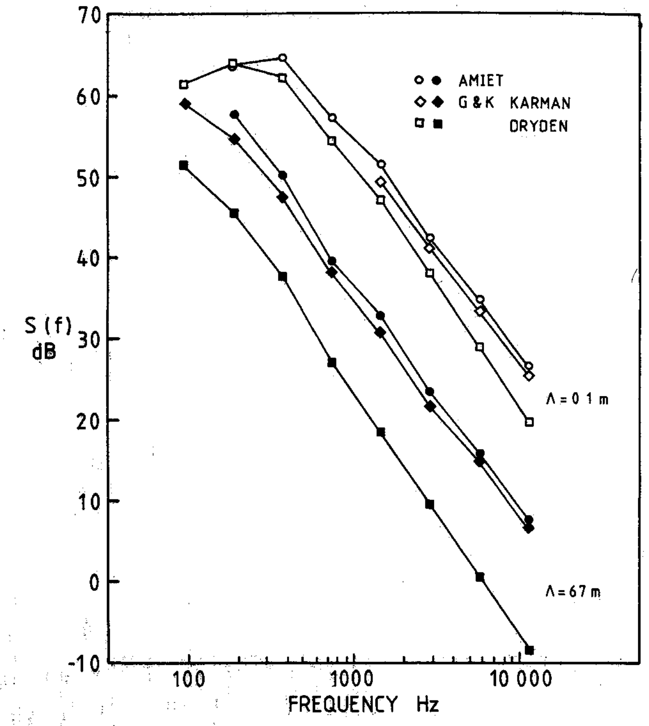

Fig 8 Effect of turbulent integral scale on rotor inflow turbulence noise calculations, UH-1; $\phi = -90$ deg, $\sqrt{\overline{w^2}} = 1$ m/s.

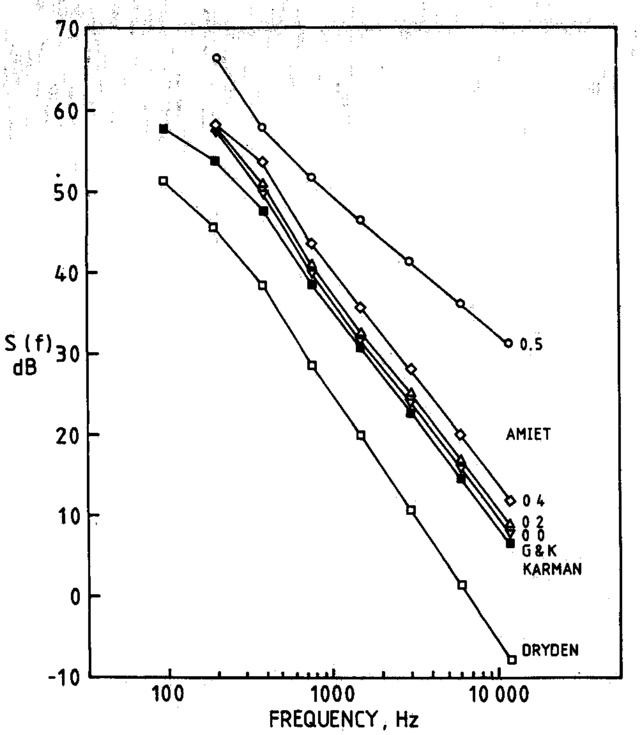

Fig 9 Effect of advance ratio on rotor inflow turbulence noise calculations, UH 1; $\phi = -60$ deg, $\Lambda = 67$ m $\sqrt{\overline{w^2}} = 1$ m/s

Figure 9 shows the effect of forward flight on inflow turbulence noise as calculated by Amiet's analysis and compared to hover calculations based on George and Kim's analysis It is notable that the advance ratio effect is not very important for cases of interest to helicopters (i e , advance ratio below 0 4) Similarly, Fig 10 compares changing advance ratio for boundary layer trailing edge noise Here the basic inputs vary, since the calculation of Kim and George uses an airfoil boundary-layer thickness correlation,[38] rather than the flat plate results incorporated in their earlier publications and those of Amiet In this boundary layer trailing edge noise case, the results again show that the effects of advance ratio are not important for values less than 0 4

As discussed previously, Amiet's computational model incorporates an accurate basic blade noise radiation directionality for the pressures normal to the blade mean line; on the other hand, the methods of George and coworkers approximate the basic directionality by a dipole normal to the rotor plane, which would be expected to underestimate the noise radiated close to the rotor plane Both analyses ignore in-plane forces and other in plane mechanisms. Figures 11 and 12 compare the directionalities for both inflow turbulence and boundary layer noises It is clear that, aside from overall differences, the directionalities are quite close except within about 10 to 15 deg of the rotor plane

Comparisons of Different Mechanisms in Different Situations

It is already apparent from the results presented thus far that the various mechanisms can each be important in different situations We have seen that inflow turbulence noise can dominate the noise radiation when the inflow turbulence is strong. On the other hand, at high frequencies either boundary layer trailing noise or tip-vortex noise can be important as can be seen from Figs 1-4 Both of these sources increase with blade angle of attack while tip vortex noise depends strongly on blade chord and is more severe for square tip shapes. Some of these dependencies are shown in Fig 13. Calculated spectra are shown for pitch angles of 10 and 15 deg for boundary layer noise and for tip vortex noise based on both square and round tip shapes for a rotor similar to that of a UH-1. Clearly, tip vortex noise is favored by high angles of attack and wide tip chords (low aspect ratio, untapered blades). On the other hand, wind turbines generally have tapered blades and we have seen that their primary noise source in the frequency range of interest is the boundary-layer trailing edge (see Fig. 3)

The relative importance of various mechanisms on a full scale helicopter configuration is an interesting, yet complex, question as various noise mechanisms exist on both the main and tail rotors Some calculations showing the effects of varying the inflow turbulence scale are shown in Fig 14 for a UH 1 helicopter main rotor The varying turbulent intensities give some idea of the variations expected between quiet nighttime conditions and typical daytime conditions They could be considerably higher in windy conditions

Next, we question the relative importance of the tail rotor as compared to the main rotor The primary added difficulty in dealing with tail rotor noise is that the tail rotor operates in

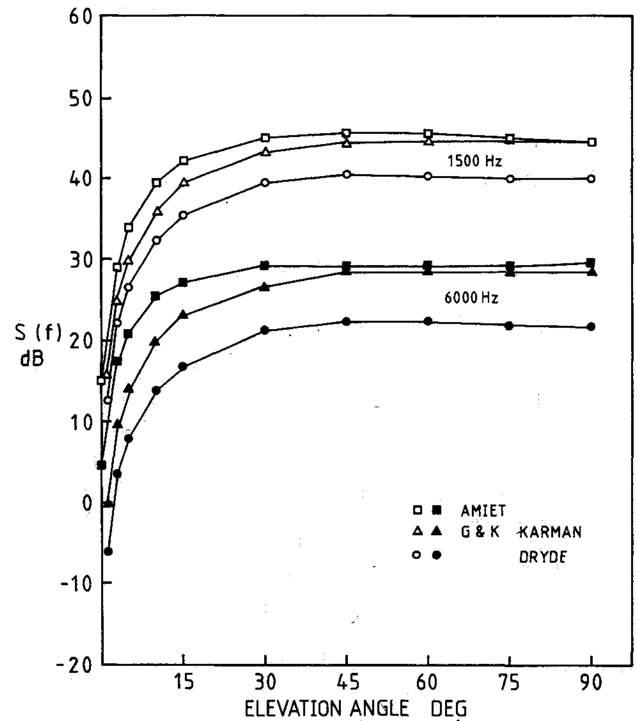

Fig 11 Directionality of inflow turbulence noise for S55 full scale rotor as in Leverton's experiment;[50] $\Lambda = 0\ 57$ m, $\sqrt{\overline{w^2}} = 1$ m/s

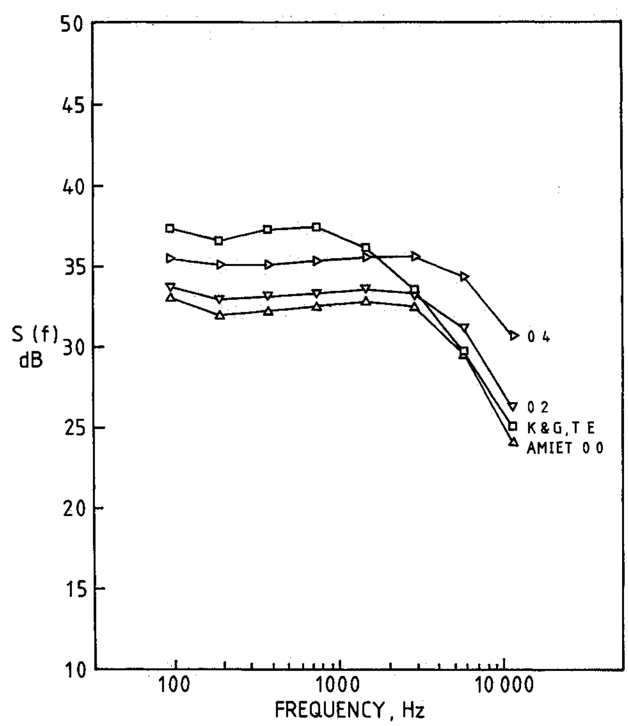

Fig 10 Effect of advance ratio on rotor trailing edge noise calculations, UH-1; $\phi = -90$ deg

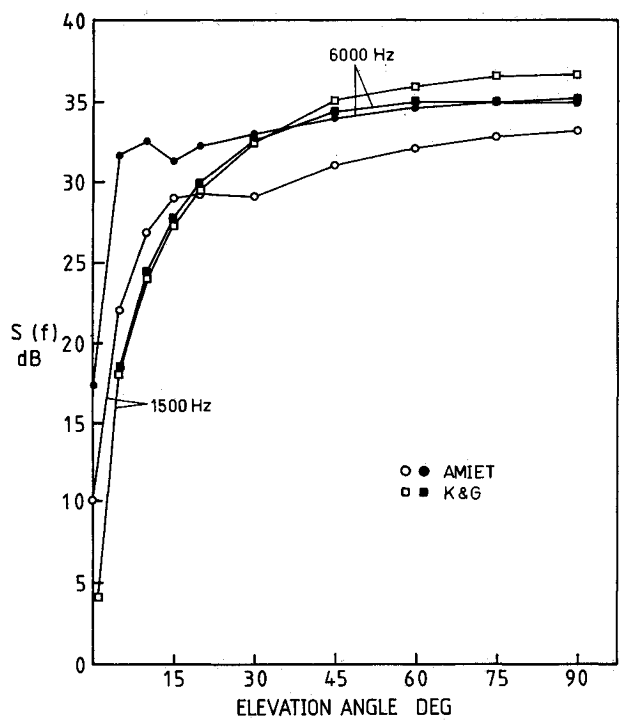

Fig 12 Directionality of rotor trailing edge noise; same rotor used as in Fig 11

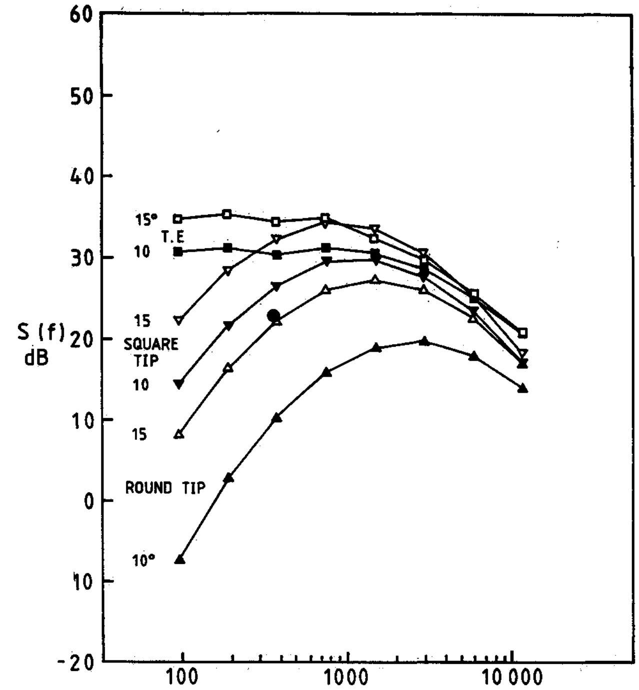

Fig 13 Comparison of trailing edge noise and tip vortex noise (with different tip shapes) calculations for ten and 15 deg rotor pitch, UH-1, $\phi = -27$ deg.

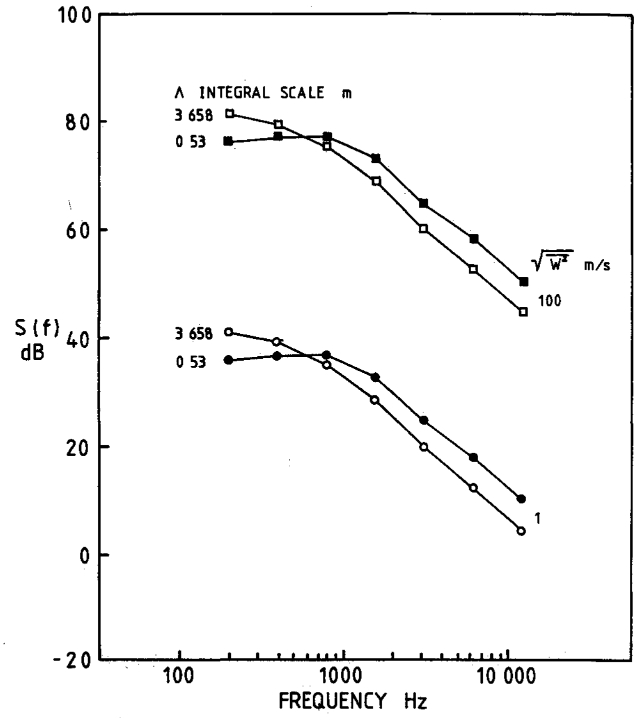

Fig. 15 Effect of main rotor wake being ingested by the tail rotor, UH 1; various assumptions for turbulent intensity and scale

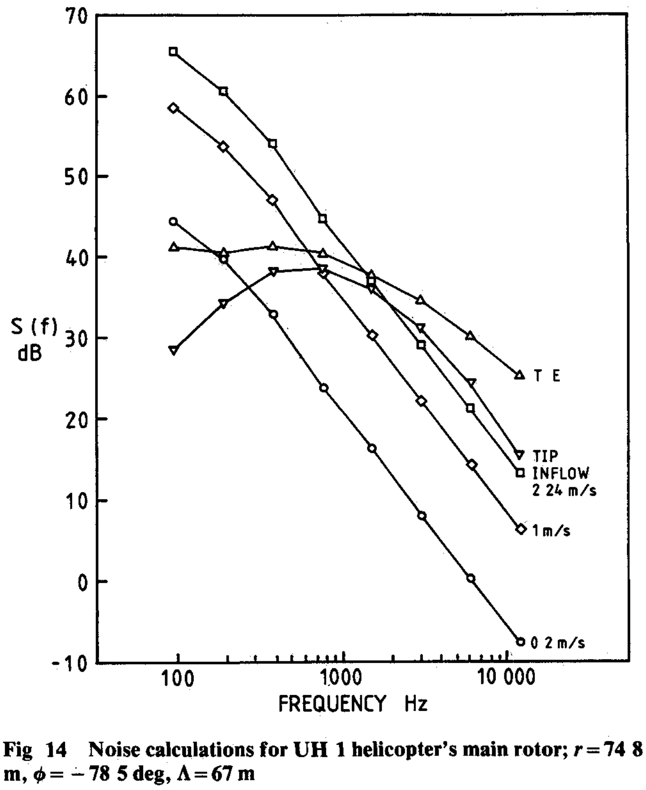

Fig 14 Noise calculations for UH 1 helicopter's main rotor; $r = 74$ 8 m, $\phi = -78$ 5 deg, $\Lambda = 67$ m

the main rotor wake, which is itself not very well understood The main rotor wake consists of a number of components: the overall downwash field, the tip trailing vortices and other vortices shed from the main rotor blades, the wakes of the fuselage, engines, and rotor hub, and the turbulence present in these flows as well as that already existing in the atmosphere The importance of wake ingestion on noise was pointed out in some experiments of Levine,[55] when a Sikorsky S-58T, operated with the main rotor wake being blown into the tail rotor, a 5 to 10 dB increase in both narrowband and broadband noise was observed Significant reductions in tail rotor noise were also reported by Barlow et al , for a redesigned OH 6A tail rotor [56] Another experimental study of tail/main rotor wake interaction noise involved wind tunnel tests of a model with variable tail rotor position and direction [57 58] Balcerak[57] made a parametric study, varying tail rotor location, fin blockage area, tail rotor rotation direction, rotor speeds and thrusts, and tail rotor pusher/tractor configuration Later, Pegg and Shidler[58] tested the same model, extending the work and emphasizing identifying the aeroacoustic mechanisms producing the noise They found approximately a 12 dB increase in broadband noise when the main rotor flow was added to the tail rotor and significant increases in harmonics under a variety of conditions These experiments are very important and point out the complexity and the need for more analytical understanding of tail rotor broadband noise sources and methods for reducing these sources

In the present study, all we can do is present a few simple calculations to show the important effects of main rotor wake ingestion by the tail rotor Figure 15 presents calculations for inflow turbulence noise due to ingestion of assumed main rotor wake turbulence The turbulence length scales are taken as the main rotor chord or radius Although these estimates range widely it is clear from comparing Fig. 16 to Fig 15 that the tail rotor ingestion of the main rotor wake is very im portant and deserves much more attention in the future

Conclusions

The understanding of and ability to predict broadband rotor noise are approaching a satisfactory state in many respects Until about ten years ago, understanding was essentially qualitative, sometimes erroneous, and several mechanisms were not even recognized As shown in this paper, the important broadband noise mechanisms are now sufficiently well understood to make predictions to within about 5 dB of experimental data This understanding should enable designers to minimize broadband noise in cases where it is a controlling factor

The calculations and comparisons shown indicate that inflow turbulence-induced lift fluctuations are the most important broadband noise source at low frequencies. This radiation can be predicted down to the lowest blade passing frequency, including the smooth peaked spectral structure, by the method of Homicz and George [15] For the higher frequencies, which are often of more practical interest, the methods of George and Kim[16] and Amiet[17] are as satisfactory and much easier to compute When the same inflow tur bulence spectrum is used, both of the methods seem to agree well with each other and with measurements over a full range of parameters except for angles within 10 to 15 deg of the rotor plane. The Karman spectrum is suitable for use in predicting the inflow turbulence noise radiating from full-size rotors However, the Dryden spectrum is more suitable to predict the indoor model rotor inflow turbulence noise where small scale turbulence is involved Further research is needed on broadband rotor noise near the rotor plane Most ex periments do not include enough inflow turbulence data to define the inputs to the analyses In particular, the effect of steam-tube contraction on generating anisotropic and large-scale inflow turbulence needs more theoretical and ex perimental attention

Boundary-layer trailing-edge noise is now well understood The analyses of Kim and George[31] and of Schlinker and Amiet[32] and the correlation of Fink[30] all appear to give results which agree reasonably well with experiments. This source was seen to be the primary broadband noise source for full scale wind turbines It is often the important noise source at high frequencies on large rotors when inflow turbulence is weak. It increases significantly with angle of attack due to the increase of boundary layer thickness

Tip vortex formation noise seems to be satisfactorily predicted, although it is not sufficiently dominant in any of the experiments to establish definitively the precise accuracy of the model of George et al ,[44,45] which uses delta wing leading edge vortex data to model the tip vortex Much more experimental data is needed on flows and fluctuating pressure on different shapes of rotors and wing tips Tip vortex noise is most important for square tips and for wide chords It probably can be reduced significantly by detailed tip shape changes, but this is presently unexplored.

The noises radiated from helicopter tail rotors remain poorly understood The main rotor wake is very complex and is itself poorly understood, although it is the primary input needed for tail rotor noise predictions

Finally, further comparisons of the mechanisms to better defined experimental measurements are still needed to establish the accuracies of analyses and enable further improvements of the broadband noise analyses and noise minimization techniques

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