Helicopter Noise: State-of-the-Art

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I. Introduction

THE helicopter has become a more and more common sight; it is now ubiquitous enough so that in populated areas it has changed from being an occasional and interesting sight and sound to being just another aircraft contributing to the overall community noise level. At present, the Federal Aviation Agency (FAA) and International Civil Air Organization (ICAO) are considering the noise measurement and certification procedures for helicopters. With the advent of noise certification, the design and operation of commercial helicopters will be influenced very heavily by noise considerations, as has been the case with large fixed-wing aircraft. Military helicopter design is also influenced by noise considerations, although audibility and detectability considerations are somewhat different than those for community noise.

There are a variety of noise sources associated with helicopters, and their relative importance depends both upon the particular helicopter design and on the criteria considered. This paper reviews helicopter external noise with particular emphasis on the noise due to helicopter main and tail rotors. The bases for annoyance and audibility are discussed. Sources of rotor noise include steady, periodic, and random loads on the rotor blades, as well as volume displacement and nonlinear aerodynamic effects at high blade Mach numbers. Either main or tail rotors can be dominant noise sources at various frequencies and observer positions.

Engine also produce noise of various types. Turbines produce inlet, compressor, turbine, combustion, and jet noise, and reciprocating engines produce intake and exhaust noise as well as noise due to structural vibrations. Engine noise will not be discussed in this review, as it is usually not as important as rotor noise for helicopters, and engine noise reduction is generally treated separately. Gearbox vibration can also contribute to external helicopter noise; however, it is primarily important to interior noise, where it is a serious problem. Gearbox noise is not a true aeroacoustic source, and it can be controlled by fairly standard industrial noise control approaches involving a source-path-receiver approach to control vibration, its transmission and acoustic coupling, and the acoustic properties of the helicopter interior.[1-3]

This paper will primarily emphasize the state of present understanding and prediction abilities for helicopter main and tail rotor noise. The particular emphasis will be on an understanding of the detailed phenomena involved rather than toward a discussion of empirical and semiempirical prediction schemes. These are, of course, very useful tools for interpolating between and extrapolating from present practices. A reader interested in such techniques is referred to the recent studies by Magliozzi et al.[4] and by Bowes[5]. Other earlier reviews of helicopter and rotor noise can be found in Refs. 6-10. Some of these treat certain topics in more depth than the present review.

II. Annoyance and Audibility

Subjective response to conventional jet aircraft noise is generally well predicted by perceived noise levels (PNdB) or a weighted sound level (dBA) with modifications to account for sound duration (e.g., EPNdB, Ref. 11). These weighted sound levels account for the fact that higher frequencies of sound are generally subjectively more annoying. For example, the frequency weighting characteristic of the dBA level is shown in Fig. 1. It is quite clear that lower-frequency components of noise are much less annoying. However, this weighting characteristic of human response can be partly or fully offset by the fact that the sound generated by an aircraft propagates for some distance through the atmosphere, undergoing frequency-dependent absorptions due to viscosity, heat conduction, molecular relaxation, and atmospheric inhomogeneties.[12-14] The order of magnitude of this attenuation in decibels per kilometer is plotted against frequency in Fig. 2.[12] The very high attenuations at high frequencies imply that frequencies above 2000 Hz or so are not likely to be important in most situations. Thus we find that the important range for annoyance tends to fall in the low to middle frequency range.

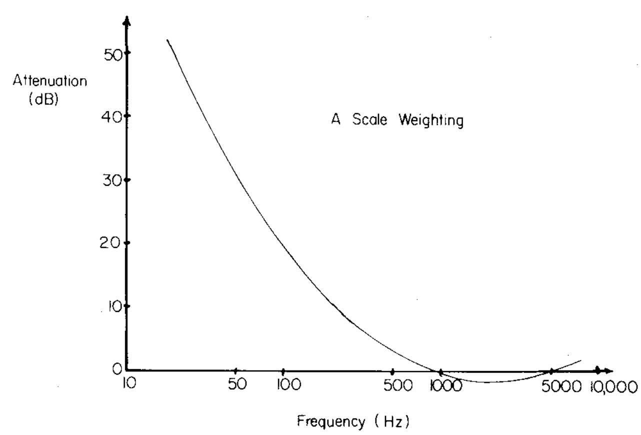

Fig. 1 Weighting for dBA scale: a typical measure of annoyance.

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Recent studies by the FAA related to noise certification suggest that the duration-weighted EPNL is a satisfactory measure of helicopter operational noise.[15] The impulsiveness of helicopter noise, due to blade slap for example, makes it more annoying than PNdB or dBA measures would indicate. However, the typical directionality of the impulsive-type sound greatly increases the duration of the sound included in the EPNdB measured during a flyover and seems to be about the right penalty for this effect.[16] This measure has been suggested for certification standards.

For audibility and detection of aircraft noise, the basic criterion is based on the acoustic energy of the aircraft's noise spectrum in critical bandwidths[17] of the ear's response. (These are very roughly ⅓-octave bandwidths.) For detection, the energy in some critical bandwidth must be both greater than the ear's threshold and not more than 5 dB below the ambient noise level in that critical band. The combination of the ear's threshold, typical background noise levels, and the effect of atmospheric attenuation over long distances tend to make audibility primarily a function of acoustic energy in the 250-500 Hz areas.[18]

For typical helicopter spectra, discussed below, the fact that the, say, 100- to 1000-Hz region is important means that significant contributions to annoyance and detectability are made by a variety of sources. These include main rotor high-order harmonics, main rotor random loadings, tail rotor low-order loading harmonics, and harmonics of main and tail rotor impulsive noise due to blade vortex interactions and high Mach number effects. So we see that, unfortunately, a large number of mechanisms are important in practice, and noise reduction must deal with all of these mechanisms.

III. Physical Bases of Rotor Noise Generation

In order to understand the mechanisms which lead to acoustic radiation from rotors, consider Lighthill's acoustic analogy. This formulation manipulates the exact equations of fluid mechanics into an apparently conceptually simple form. Beginning from the equations of mass and momentum conservation, but allowing for mass sources and applied forces in the fluid, Lighthill[19] showed that those equations could be put in the form of a wave equation on the left-hand side, with all other terms on the right-hand side:

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_i{}^2} = \frac{\partial Q}{\partial t} - \frac{\partial F_i}{\partial x_i} + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{1}$$

where

ρ = density
c_0 = undisturbed speed of sound
Q = mass source strength, mass/volume × time
F_i = force/volume = momentum/volume × time
T_{ij} = Lighthill stress $= \rho u_i u_j + (p - c_0^2 \rho)\delta_{ij} - \sigma_{ij}$
σ_{ij} = viscous stress tensor

Lighthill's contribution was the simplifying concept of considering the right-hand side of this equation as known source terms. The right-hand side is rarely known exactly but often can be estimated satisfactorily. If the right-hand side is written as a known function $g(x_i,t)$, then the inhomogeneous wave equation (1) can be simply solved for the radiated sound. In this formulation, we consider the moving rotor blades and their associated flowfields as being comprised of 1) moving sources and sinks to model the motion of the rotor blade volumes, 2) moving forces to model the motion of the forces between the blades and the fluid, and 3) a moving T_{ij} distribution which accounts for the nonlinear flow effects which have been moved to the right-hand side of Eq. (1) in order to leave a wave equation on the left-hand side.

T_{ij} can include such effects as turbulence, compressible flow and shock-wave effects, nonisentropic effects, and viscous flow effects. When using Lighthill's analogy in the form of Eq. (1), the various source and force terms are generally assumed to act as point sources or to be distributed over the blade mean rotational plane or the mean helical surface swept out by the rotor or propeller motion. If a more complete representation of moving bodies is desired, it is generally better to work with the Ffowcs-Williams and Hawkings[20] form of the Lighthill equation. Here any arbitrarily moving body can be considered to be comprised of moving surfaces defined by $f(x_i,t) = 0$ with no net flow through them. [$f(x_i,t)$ is assumed to be scaled such that $|\Delta f| = 1$.] These surfaces enclose volumes of stationary fluid, and, in order to leave this stationary fluid behind them as they move, they must supply a mass source per unit area of $\rho_0 v_i \hat{n}_i \mathrm{d}S$, alternatively expressed as a source strength per unit volume of $Q = \rho_0 v_i \hat{n}_i \delta(f)$, where v_i is the velocity of the surface, $\hat{n}_i$ is the unit vector normal to the surface, and $\delta(f)$ is the Dirac delta function. Similarly the pressure and viscous forces on the surface are given by $p_{ij}\hat{n}_j \mathrm{d}S$, which corresponds to a force per unit volume of $F_i = p_{ij}\hat{n}_j \delta(f)$. With this formulation, the Lighthill equation can be written as

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial}{\partial t}[\rho_0 v_i \hat{n}_i \delta(f)] - \frac{\partial}{\partial x_i}[p_{ij}\hat{n}_j \delta(f)] + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{2}$$

where

$$p_{ij} = p\delta_{ij} - \sigma_{ij}$$

Since either Eq. (1) or (2) can be written in the inhomogeneous wave equation form

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_i \partial x_j} = g(x_i,t) \tag{3}$$

its formal solution can be written as

$$\rho - \rho_0 = \frac{1}{4\pi c_0^2} \int\int\int \mathrm{d}^3 x_i' \int \mathrm{d}t' g(x_i',t') - \frac{\delta[t - (R/c_0) - t']}{R}$$

where

$$R = |x_i - x_i'| \tag{4}$$

or, using the properties of delta functions, this may be written either in terms of retarded times

$$\rho - \rho_0 = \frac{1}{4\pi c_0^2} \int\int\int \mathrm{d}^3 x_i' \frac{g[x_i', t - (R/c_0)]}{R} \tag{5}$$

or it can be expressed in terms of an integral over past times of contributions on a contracting spherical surface Ω of radius $R = |x_i - x_i'| = c_0(t - t')$, implying that g is evaluated on this surface $x_i'(t')$ (see Fig. 3). Then

$$\rho - \rho_0 = \frac{1}{4\pi c_0} \int \mathrm{d}t' \int\int \mathrm{d}^2\Omega \frac{g[x_i'(t'), t']}{R} \tag{6}$$

From this form in particular, it is easy to see how the different terms in the right-hand side of Eq. (1) or (2) contribute to far-field sound.

Stationary sources at a fixed position in space clearly contribute only if they are unsteady. A moving volume can be considered either as a moving steady source and sink array or as a spatially fixed distribution of sources being turned off and on. For example, a sinusoidal source variation moving at a speed V can be written in the form of a moving wave

$Q = Q_0 \exp[ik(x-Vt)]$ or, equivalently, as an array of unsteady sources with time variation $\exp(-ikVt)$ as $Q = Q_0 \exp(ikx)\exp(-ikVt)$. Both of these points of view have been variously applied to both source and force radiation.

In order to understand the radiation due to a moving volume, we note that for a closed constant volume the sum of the positive source strength associated with the front of the body and the negative source (sink) strength associated with the rear of the body is zero. However, since the time changes during the time integration of Eq. (6), the net source and sink strengths $g(x_i', t')$ in the integrand may be different from zero due to changes in blade orientation. Also, as the body moves with a relative velocity closer the the speed of sound toward the observer, the Ω surface will spend more and more time passing through the body, allowing more time for source/sink strengths to vary due to the ensuing blade motion. Thus these effects become more and more important at higher blade-observer relative Mach numbers and are important contributors to high-speed blade bang. These effects have recently been studied extensively by Farassat,[21-23] Hanson,[24] Hawkings and Lowson,[25] and others. These effects, which are fundamentally noncompact source effects, were not appreciated in many earlier studies where compact sources were assumed at the outset.

When considering sound due to moving forces, we again find a similar effect. The force terms [F_i in Eq. (1) or P_{ij} in Eq. (2)] appear to be differentiated in the x_i direction. Thus the variation of the force components in their own respective directions contribute to sound. Then, considering the Eq. (5) form of the solution, we see that, unless F_i varies during the time interval of passage of the Ω surface through the blade, the x_i integration of $\partial F_i/\partial x_i$ will give just F_i evaluated between its limits, which are each zero as F_i vanishes off the blades. Thus, here too, contributions to sound of unsteady forces become more important as the blade moves closer to sonic velocity relative to the observer, as then the retarded time interval associated with the x integration becomes larger. However, the large lift components of the blade forces are only distributed in the lift direction over the small thickness distance of the blade, Also, helicopter rotor blades do not usually move at appreciable velocities in the lift direction. Thus, the significant contributions of lift components to noise do not increase as rapidly with velocity as the source terms which we considered earlier. However, the drag components of the blade forces are more widely distributed in the drag direction, which is also the direction of their motion. Thus noncompact drag forces will become relatively more important as blade Mach numbers increase. This effect has not yet been treated extensively, but indications are that it is not very important for helicopter rotors.[26]

The last of the three terms on the right-hand side of the Lighthill equation is the derivative of T_{ij}, where $T_{ij} = \rho u_i u_j + (p - c_0^2)\delta_{ij} - \sigma_{ij}$. The terms in T_{ij} are, respectively, nonlinear flow contributions, nonisentropic effects, and viscous stress effects. Again, following similar arguments as with the force terms, the contributions are important only if the T_{ij} components in the observer's direction vary significantly due to either blade rotation or unsteadiness during the passage of time of the Ω surface through the disturbed flow region. In Ref. 27, Kitaplioglu and George have calculated radiation from a simplified model of a shock wave suddenly appearing and disappearing on a blade. The effects of the continuous gradients in the flow may also be important. Our order-of-magnitude estimates show that the acoustic contribution of an unsteady but continuous T_{ij} change is independent of the distance over which the T_{ij} change occurs. This is so because, although the gradients' magnitudes are decreased, the retarded time interval during the integration lengthens and compensates. Thus other noncompact T_{ij} effects besides shock waves are being investigated for high-speed advancing rotor blades.

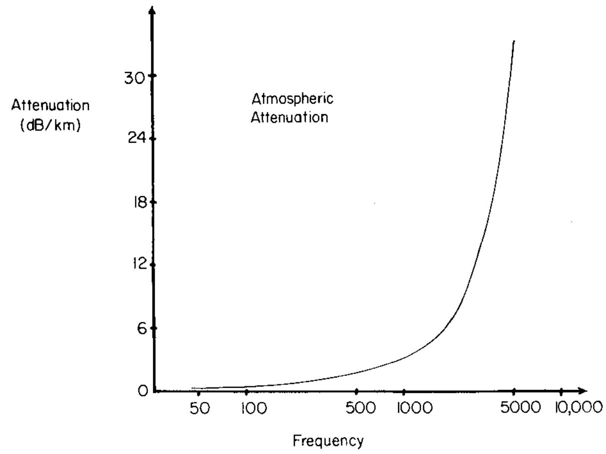


Fig. 2 Attenuation of sound in the quiescent atmosphere (per kilometer): 20°C, 50% relative humidity.[12]

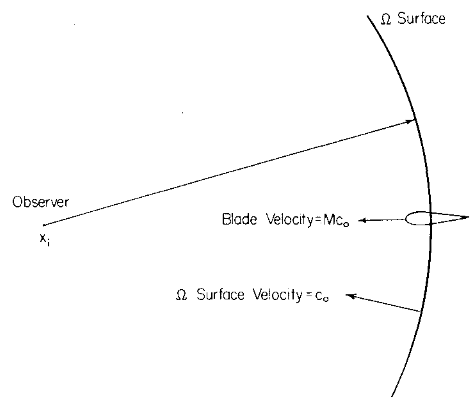
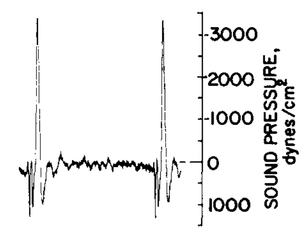


Fig. 3 Contracting spherical surface of integration of Eq. (6).

Fig. 4 Measured pressure-time history of UH-1H acoustic signal: 115 knots, 800-ft/min descent (from Ref. 28).



IV. Typical Helicopter Noise Time Histories and Spectra

A helicopter noise time history (Fig. 4) or spectrum (Fig. 5) is made of two types of sounds which generally occur simultaneously: 1) a periodic part with the fundamental frequency originating from the blade passing interval and which leads to line spectra at the fundamental frequency and its harmonics; and 2) a nonharmonic or random signal which produces a continuous but possibly quite peaked spectrum.

Referring to Fig. 4, the periodic impulses in this signal[28] are due to the effects of the blade steady force and volume effects and to periodic blade load fluctuations due to blade-vortex interactions and other periodic blade loading variations. In the spectrum[28] shown in Fig. 5 (corresponding to different flight conditions), such periodic effects give rise to quite distinct lines in the spectrum extending to high harmonics of the blade passing frequencies. Tail rotor harmonics can also be important in helicopter spectra.[6,16] They tend to have maxima in the area of the spectrum which is most important to annoyance and audibility.

Between the impulsive parts of the time domain signal, a more random background is apparent. This part can be the

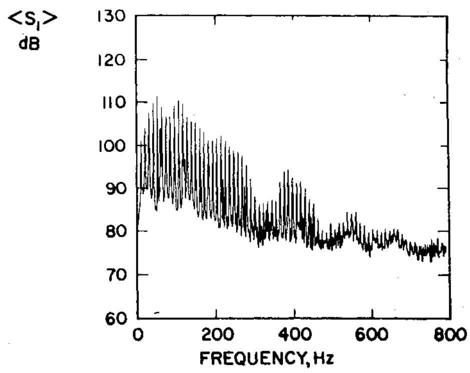


Fig. 5 Spectrum of acoustic signal of UH-1H: 80 knots, 400-ft/min descent (from Ref. 28).

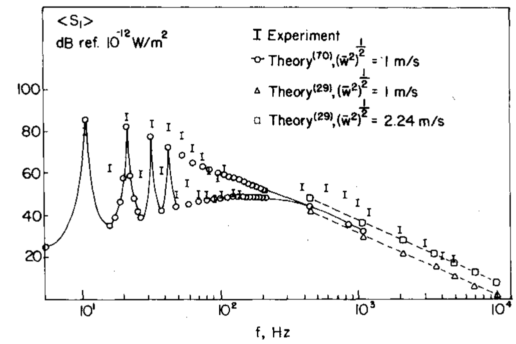


Fig. 6 Measured acoustic spectrum from a hovering helicopter and calculated spectra based on atmospheric turbulence induced random loadings on main rotor.[27]

primary noise source in the absence of extensive impulsive noise, as in hover, for example. This part of the signal is associated with randomly varying blade forces. The spectrum corresponding to random loading can be smooth, or it can exhibit a peak-valley but continuous structure due to loadings which have some degree of coherence between several blade passages. For example, an experimental spectrum and corresponding calculations based on random loadings due to atmospheric turbulence are shown in Fig. 6.[29] Here the lower-frequency part of the spectrum is generated by blade interactions with large-scale turbulent components which are intercepted several times by the blades before being completely drawn through the rotor plane.

For typical present helicopters and operations, impulsive noise is important for approaching helicopters or those in forward descending flight, whereas broadband noise or tail rotor harmonics are important overhead or in hover. Engine noise can also be of importance but is reduced relatively easily by mufflers or acoustically treated ducting.

V. Sound Due to Blade Forces

In this section, we will review the present state of knowledge regarding noise generated by forces.

A. Steady Forces

The radiation due to steady thrust (lift) and torque (drag) forces was analyzed by Gutin in 1936.[30] He modeled the forces as constant but moving point dipole acoustic sources with a resulting discrete spectrum which decays very rapidly with frequency. The Gutin theory predicts the first few harmonics of rotor noise correctly but, it severely underestimates the measured high-frequency harmonics, especially for low tip speeds. This is particularly a problem for helicopters when the main rotor fundamental frequency is on the order of 15 Hz, and only the higher harmonics are important for annoyance and audibility.

B. Periodic Blade Loadings: Rotational Noise

The problem with the Gutin theory was resolved considerably later when Lowson and Ollerhead[31] and Wright[32] analyzed the radiation due to azimuthal variations in blade loading which are steady in time. They found that the higher harmonics of the blade loading spectrum are extremely important to high-frequency discrete spectrum rotational noise. In fact, at high frequencies the sound from even very small-amplitude loading harmonics dominates that due to the steady loading analyzed by Gutin. Although these analyses related the high harmonics in the noise spectra to high-frequency blade loading harmonics, they do not explain the origin of all the measured[33] or inferred high-frequency loading harmonics. For lower-order loading harmonics, one can invoke forward flight, fuselage effects, cyclic blade motions, and cyclic blade incidence changes, but it has been generally necessary to use experimental or empirical high-frequency loading laws to get agreement with experiment. In addition, measurement spectra show a peak-valley as well as a line structure, implying random as well as periodic loadings. Some theoretical work on reducing rotational noise by tailoring blade load distribution has been reported in Ref. 34.

For some helicopters, tail rotor rotational noise can be more important than main rotor noise in certain parts of the spectrum. This is typically from 100 to 500 Hz, a range which is very important to audibility and annoyance. Tail rotors tend to produce a large number of rotational harmonics and combination tones with the main rotor, as their inflow is generally quite nonuniform due to ingestion of the periodically distorted main rotor wake and the influence of the nearby tail boom or pylon the on the flow.[35,36] However, reduction in tail rotor tip speed and repositioning the tail rotor relative to the main rotor wake are quite useful in reducing this radiation. Much work remains to be done in this area.

C. Blade-Vortex Interactions

One characteristic of rotor noise time histories in many flight conditions is the impulsive peaks occurring at the blade passing time interval. When Fourier analyzed, these peaks lead to a large number of slowly decaying harmonics, as shown previously in Fig. 5. It is now well established that some of these impulsive sounds are due to the rapid load variations caused by a rotor blade passing close to or through a tip vortex trailing from the same or another blade. Analyses of the basic aeroacoustic interaction between a blade and vortex have been carried out by Widnall[37] and Filotas[38] assuming classical attached flow response of the blade to the additional velocity of the vortex. However, due to the complexity of the trailing tip vortex's geometry and of the blade's actual response, we are far from being able to predict this noise a priori for given helicopter operating conditions. A number of experimental and analytical studies have greatly clarified the conditions when these interactions occur.[28,39-43]

Even for a single rotor, a great number of blade-vortex interactions can occur, depending on flight speed and rate of descent. As present aerodynamic wake calculation methods can give some indication of when blade-vortex interactions occur,[39] this may possibly allow designers to avoid those conditions. Another approach to this problem is the modification of the rotor tip region in such a way as to diffuse the tip's trailing vortex. Then the blade-vortex interaction will be more gradual, reducing the impulsive forces and sound. Tip blowing, spoilers, split tips, and ogee tips have all been tried. Considerable success has been shown with practical subwings and the related ogee tips.[40,44,45]

D. Stall and Shock Effects in Blade-Vortex Interactions

It has also been recognized that during blade-vortex interactions other effects can occur in addition to the loading variations due to classical subsonic attached flow. Unsteady stall can be caused by local flow incidence changes, and shock-wave formation can be caused by increased flow velocity.[39,43,46,47] These phenomena give loadings that are drastically different from those found from classical analyses and also exhibit considerably more rapid changes in the loading. These rapid time variations in loading generate strong acoustic radiation. These aeroacoustic interactions have been well established experimentally, but little quantitative prediction has been attempted. Here, as in the basic blade-vortex interaction, the best noise control technique undoubtedly lies in trying to devise a way to eliminate the close passage of a blade and a concentrated vortex rather than in changes which would only affect the details of the aeroacoustic interaction.

E. Radiation Due to Vortex Streets and Related Phenomena

Any fluctuating forces on a body give rise to sound radiation. One of the first such mechanisms identified was the von Kårmån "vortex street" phenomenon occurring on circular cylinders in certain Reynolds number ranges. Although blades are generally streamlined shapes, similar load fluctuations associated with nearly periodic vortex shedding occur on them in certain Reynolds number ranges. The nearly periodic nature of the fluctuations gives rise to a continuous but peaked acoustic spectrum shape often identified as "high-frequency broadband noise." The excitation mechanism and the resulting radiation have been widely studied.[48-54] Evidence based on simple experiments indicates that this source occurs only when the boundary layer on at least one side of the airfoil is laminar.[48] Full-scale helicopter rotors essentially always have fully turbulent boundary layers at the trailing edge, and thus this mechanism is generally unimportant in their measured spectra. However, some full-scale but quite low-tip-speed experiments[55] do seem to exhibit some residual constant Strouhal number hump in the radiated spectrum, even when turbulent boundary layers would be expected on the blades. The turbulent boundary layer's direct contribution to radiation is also discussed in relation to trailing-edge noise in Sec. V.F.

F. Self-Generated Turbulent Loading

Other random blade loadings can be generated by the interaction between a rotor blade and the turbulence generated by that blade's own motion. The most obvious example is the turbulent boundary layer on the blade surfaces. Turbulence passing over an infinite flat surface is a quite weak sound source, but, when turbulent eddies pass over the trailing edge of a blade, somewhat more sound is radiated. Understanding of the details of this interaction is still in a state of flux both experimentally and theoretically. Various analyses[56-62] differ on items such as whether to apply the Kutta condition and its importance and on the locations, convection speeds, and types of multipole sources.[63] Amiet's[59,60] model of radiation from a fixed blade is attractive because it is complete in itself and does not need additional modeling or empiricism but only experimentally determined surface pressure spectra far from the edge. According to this analysis, turbulent boundary-layer noise is unlikely to be important compared to incident turbulence noise, which is discussed in Sec. V.G. However, a recent analysis and calculations by Y. N. Kim at Cornell University (private communication) indicate that trailing-edge noise can be important relative to incident turbulence noise at high frequencies under conditions when ingested atmospheric turbulence is weak and of large integral scale.

Several empirical correlations of experimentally measured "trailing-edge noise" are available in the literature[64,65] but these correlations, some of which were derived for jet-flap-type configurations, were found in our studies at Cornell to overpredict helicopter rotor noise spectra by over 15 dB. Other sources of turbulence noise from rotor blades can be due to turbulence in locally stalled regions[47,66] or due to tip flow effects.[8,67] In hover, the tip trailing vortex can move upward behind a blade and even pass over the following blade before being swept downward in the rotor wake.[6] The resulting flow incidence changes can cause local blade stall. The effect of local stall on acoustic radiation was studied experimentally for the steady interaction between a stationary blade and incident trailing vortex by Paterson et al.[47] It is likely that this source is not as important in the forward-flight helicopter case where the unsteady stall effects on overall blade forces would probably overshadow the noise associated with the turbulence-surface interactions in the separated flow.

The importance of turbulence in blade tip flows has not been fully resolved; it has been discussed by Lowson in Ref. 8. Several experiments have been reported with varying results due to tip shape modifications on rotors.[53,68] The causes of the measured differences were not determined unequivocally; they may or may not be related to the blade's tip flows. Blade tip shapes also affect trailing tip vortices, and also any trailing-edge noise could conceivably have been affected by tip modifications.

G. Noise Due to Turbulent Inflow

An important source of the random part of rotor noise is the fluctuating loading associated with ambient inflow turbulence. Turbulent upwash fluctuations lead to unsteady load fluctuations, which radiate sound. The lower frequencies are generated by interactions with larger-scale turbulent eddies, and higher frequencies by interaction with smaller eddies. As the larger eddies take a substantial time to be convected through the rotor, the blades interact a number of times with a large eddy, leading to a quite peaked but continuous low-frequency part of the spectrum, as shown in Fig. 6. The incident turbulence may be due to wake recirculation for helicopters near the ground, to ambient atmospheric turbulence, or to passage through the turbulent wake of the same or other blades. Blade wakes are normally swept out of the rotor plane under lifting conditions, but, if they are not, up to 10 dB noise increases have been measured in experiments.[69] Tail rotors typically ingest the turbulent wake of the main rotor, causing additional random tail rotor loading and radiation of broadband noise, as well as the additional harmonic noise discussed in Sec. V.B.

Ingested atmospheric turbulence can make a significant contribution to nonimpulsive helicopter rotor noise and has been analyzed for isotropic incidence turbulence in Refs. 29, 70, and 71. The predicted spectra are quite close to measured hover results, although slightly low, as shown in Fig. 6. This is possibly due to the neglect of the anisotropicity of the distorted inflow, as sketched in Fig. 7. This anisotropic inflow has been demonstrated experimentally by Hanson[72] for compressor inlets, and Pegg et al.[73] have measured the corresponding reduction of radiated sound for propellers in forward flight. This effect has not been incorporated into helicopter rotor noise analysis to date. There is a sore need for experiments on rotor-turbulence interaction where turbulent inflow properties and acoustic data are measured simultaneously.

VI. Sound Due to Blade Volume

The first analysis of thickness effects on rotating radiated sound was made by Deming in 1938 based on a simple piston-in-wall formulation.[74] His analysis is essentially complete for a simple stationary propeller with symmetric blades, but he makes some rough approximations regarding blade profile shapes. Deming's analysis is not easily extended to helicopters in forward flight, general blade shapes, etc., and more sophisticated analyses have recently appeared. These have generally been based on the Ffowcs-Williams and Hawkings formulation of sound due to moving bodies, which was discussed in Sec. III. Farassat,[21-23] Hawkings and Lowson,[25] and Hanson[24] have treated the high-speed-blade case with notable success. Their analyses seem to agree fairly close with

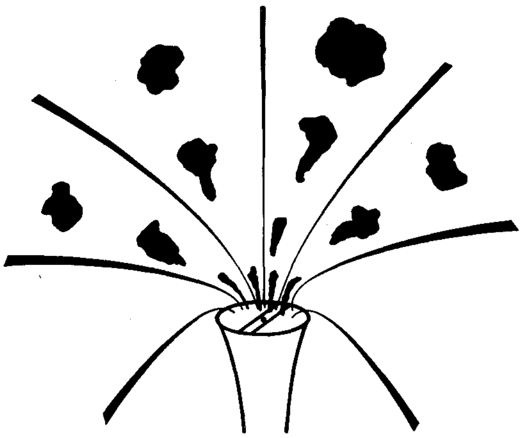


Fig. 7 Sketch of distortion of initially isotropic turbulence being ingested by a rotor.

experiments,[21,25,28] although some discrepancies are still apparent, particularly for high advancing blade Mach numbers. The primary difficulty in applying these analyses to rotor noise reduction is the complexity of the computer calculations required. The most recent approaches of Hanson and of Farassat are perhaps the most straightforward.

VII. Sound Due to T_{ij} Terms

The Lighthill stress term T_{ij} which is often loosely called the quadrupole term, contains quite a few different mechanisms. Perhaps the best known effect is predominant in jet noise, where turbulence generates self-noise due to the contributions of turbulent velocities to $\rho u_i u_j$. If u_i is expressed as $U_i + v_i$, where U_i is the mean but possibly unsteady flow and v_i is associated with turbulence, then

$$\rho u_i u_j = \rho U_i U_j + \rho (U_i v_j + U_j v_i) + \rho v_i v_j$$

The last term represents the quadrupole source effects due to turbulence, whereas the second term originates in the interaction between the mean flow and turbulent velocities. Ffowcs-Williams and Hawkings[75] showed the potential importance of this mean-flow-turbulence interaction, and some further investigations of these effects have been reported for compressors and axial fan geometries.[76,77] This effect seems to become important only for transonic blade speeds, and it seems unlikely to be as important as non-turbulent effects for high-tip-speed helicopter rotors.

The unsteady mean flow effect seems to be important for helicopter rotors. The $\rho U_i U_j$ term and the $p - c_0^2 \rho$ also in T_{ij} include what are traditionally thought of as transonic flow effects such as shock waves and high local flow velocities. This area is only beginning to be investigated at present. In a recent paper, Kitaplioglu and George[27] consider the far-field radiation from a model of instantaneous shock formation and disappearance. Their order-of-magnitude estimates show that, for instantaneous flow changes, the steep gradients associated with shock waves are more important than the more gradual flow gradients elsewhere on the blade. However, if the time variations are more gradual, estimates show that overall changes in T_{ij} are important regardless of whether they occur in thin or discontinuous regions such as shocks or whether they are spread out in the flow around the blade. Recently Schmitz and Yu[26], Hanson, [78] and Hawkings[79] have begun analyzing the noise due to quadrupole effects on rotors.

There are several causes for changes in T_{ij} which will contribute to far-field sound. First, analogous to the blade volume case, the geometry (location) of the blade and associated flowfield change during the integration of Eq. (6). This effect might be present even if T_{ij} were constant in blade-fixed coordinates. Calculations of this effect would involve the same sort of complicated geometrical computation as in the blade volume case discussed in Sec. VI. A second effect is the time variation of T_{ij} in blade-fixed coordinates due to the changing flowfield over a rotor blade in forward flight where the relative velocity over the blade can vary cyclicly from Mach numbers of, say, 0.5 to 0.9. As the blade passes in and out of supercritical flow conditions, substantial flow changes such as the formation and decay of shocks occur.[80] A third cause of T_{ij} variations can be the passage[46] of a blade near or through a trailing vortex. Tangler[43] and Ham[46] have shown that this passage can lead to rapid and substantial flow changes or shock formation. All three of these effects remain to be investigated in detail.

VIII. Status of Prediction Methods

A number of methods exist to predict the noise of complete helicopters. As should be apparent from the preceding discussions, there are many noise sources which are not yet sufficiently well understood to be included in prediction schemes. The existing schemes are generally based on some of the available theoretical understanding but necessarily include liberal dose of empiricism where needed. Two recent reports by Magliozzi and coauthors[4,81] and one by Bowes[5] consider overall helicopter noise prediction, including methodologies for engine as well as rotor noise. In the area of rotor noise, various other aspects of rotor noise prediction are treated in Refs. 8, 35, and 82-87. However, prediction methods are fairly similar, being primarily based on various semiempirical correlations. For example, most schemes use some form of the Lowson and Ollerhead[31] or Wright[32] rotational noise theory but based upon empirical azimuthal load fluctuations. In order to predict so-called broadband noise, other correlations are used, such as that of Widnall.[84] Recently, some progress has been reported on the scaling of high-frequency constant Strouhal number broadband noise spectrum peaks.[88] The available analytical approaches to production of midfrequency random noise due to inflow turbulence[29,70,71] have not yet been incorporated into noise prediction methodology.

Very little can be done in the way of general prediction schemes for impulsive noise. The locations of blade-vortex interactions can be roughly predicted but not closely enough to allow aeroacoustic predictions. In the case of high-speed noise due to volume displacements, Farassat's[21-23] or Hanson's[24] computational approaches can be used to look at specific geometries and flight conditions.

Present prediction methods seem to be able to predict helicopter spectra to within 5 to 10 dB. In one sense, this is not too discouraging, as most hover experiments, for example, tend to include on the order of 5 dB of scatter, probably due to fluctuations in wind and turbulence in the usual outdoor tests. However, from another point of view, a 6 dB error corresponds to a factor of 2 error in the sound pressure and thus in the magnitude of the sound generating mechanisms. This discrepancy is quite serious and calls into question even whether the correct mechanisms are being considered in the prediction. Also, errors of this magnitude make designing to a specified noise level nearly impossible.

IX. Noise Reduction Techniques

Noise reduction techniques are closely related to noise prediction. As we have seen, a variety of sources can be of practical importance for helicopters, and we need to know which ones are dominant and how they depend upon design and operating parameters in order to be able to reduce them.

The velocity dependence of all rotor noise mechanisms is very strong, and, as a result, a primary noise reduction technique is a reduction in rotor tip speed. This reduces rotational noise due to the slower source motion, reduces

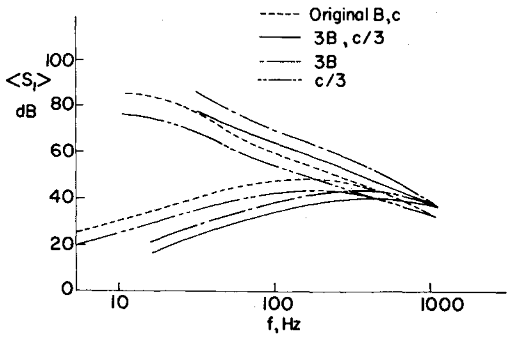


Fig. 8 Comparison of turbulent inflow noise spectra envelopes for changes in number of blades B and blade chord c.[89]

random noise by reducing loadings due to velocity fluctuations, and reduces high Mach number effects by reducing advancing blade Mach numbers. However, tip speed reduction is limited by adverse effects on helicopter performance and on autorotative capability.

Other noise reduction techniques involve reduced disk loading, changes in blade number, area, twist, and shape. However, some of these parameters can have opposite effects on different mechanisms. A study of the effect of various rotor and turbulence parameters on turbulent inflow broadband noise was presented in Ref. 89. As an example, the effects of blade number and chord on sound spectrum are shown in Fig. 8. Tradeoffs must be considered. For example, an increased number of identical blades can increase turbulent inflow noise but reduce and raise the frequencies of rotational noise. Thus tradeoffs must be made based on knowledge of which noise mechanisms are dominant for the particular aircraft. Some discussions of reduction techniques based on particular models of noise reduction studies are presented in Refs., 5, 8, 81, 89, and 90. Two recent parametric helicopter noise reduction studies are presented in Refs. 91 and 92.

Several programs which have modified existing helicopters for lower sound output have been reported.[4,87,93,94] These have used primarily lower main and tail rotor tip speeds but higher solidity, along with gearbox and engine acoustic treatments. In the OH-6A[93] and the HH-43B[94] programs, noise reductions ranged from 5 to 20 dB in different frequency ranges.

X. Conclusions

As we have seen, helicopter noise typically involves a large number of noise sources, and many of them can be important to annoyance and audibility. Generally, when impulsive noise due to blade-vortex interactions or due to high advancing blade Mach numbers is present, it dominates other sources. When impulsive noise is not dominant, as in hover, for example, then periodic and random loadings on main and tail rotors are important sources.

The full range of mechanisms which can contribute to rotor noise through blade volume, force, and Lighthill stresses has been reviewed. Most mechanisms are understood to some extent but not well enough to be incorporated into accurate prediction schemes. However, most of them are understood well enough so that, once one knows which source is important, one can usually devise methods of reducing its radiation. This may be by adjusting parameters such as tip speed and solidity, by designing to prevent blade-vortex interactions and unsteady shock formation, or by changing details such as blade tip shapes, etc. High-speed impulsive noise can be essentially eliminated by reduced flight speed operations when necessary. Blade-vortex interaction noise can be similarly avoided by choice of flight speed and descent rate in some cases. Much work remains to be done on many of the sources before we will be able to make substantial improvements in overall noise-performance tradeoffs.

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