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RESEARCH ON HELICOPTER ROTOR NOISE

Final Report

A. R. George

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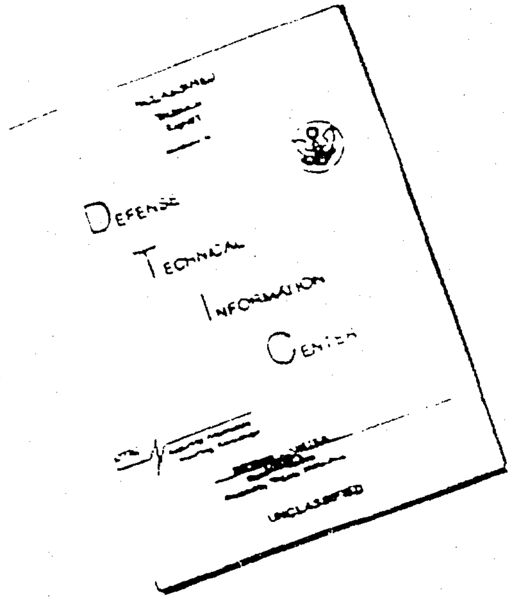

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Research was conducted on aspect of noise generation by helicopters. A general review of helicopter noise was prepared and published as one part of the work.

Methods were developed for the analysis of high frequency broadband noise from rotors. Physical and analytical approximations were devised which allow practical calculation of noise from various loading mechanisms. Atmospheric — Cont.

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turbulence noise was investigated including some effects of inflow distribution. A method for predicting trailing edge noise for rotors was developed. The results show that trailing edge noise can be quite important at high frequencies when the small scale components of ingested turbulence are weak compared to those of the blade boundary layer turbulence.

In the area of high speed noise from high Mach number advancing blades the research was primarily concentrated on the radiated sound from the Lighthill stress associated with the occurrance of unsteady shock formation and disappearance on advancing transonic rotor blades. A simplified model of an impulsively started and stopped shock was used as the known near field in order to find the far field radiation.

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1. STATEMENT OF PROBLEMS STUDIED AND INTRODUCTION

The goals of the research undertaken under this contract were to develop quantitative understanding of the various noise mechanisms and reduction techniques for helicopter rotors. Analytical and computational methods were developed to predict the noise from several of the more important rotor noise mechanisms. The results of these analyses and computations were compared to other researcher's experiments and examined for noise reduction implications.

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 (1) 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:

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

where

ρ = density

c_o = the undisturbed speed of sound

Q = mass source strength, mass/volume • time

F_i = force/volume = momentum/volume • time

T_{ij} = Lighthill stress = $\rho u_i u_j + (p - c_o^2 \rho)\delta_{ij} - \sigma_{ij}$

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 satisfactorily estimated. 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 flow fields as being comprised of

i) moving sources and sinks to model the motion of the rotor blade volumes,

ii) moving forces to model the motion of the forces between the blades and the fluid, and

iii) a moving T_{ij} distribution which accounts for the nonlinear flow effects which have been moved to the right hand side of equation (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, non-isentropic effects and viscous flow effects.

The sounds due to forces may be conveniently divided into those due to steady or periodic loadings and those due to random blade loadings. Both of these classes of loadings can be important but the origins of the many different types of random loads and the theoretical prediction of resulting radiated sound are generally less well understood. Progress on several of these mechanisms was made during the present contract.

The sound radiated by the motion of blade volumes, forces, and flow changes becomes important at high advancing tip Mach numbers and is often called high speed noise. A decade ago this noise was not understood but recently has been studied extensively by other researchers as well as under this grant. In the last few years the large effects of the T_{ij} due to shock waves on high speed noise have become appreciated and our work under this contract was primarily concentrated in this area.

Thus the research under this contract focused on three areas in particular:

(1) Broadband rotor noise due to random loadings including the effects of inflow turbulence and trailing edge noise,

(2) High speed noise due to volume, forces, and unsteady shock waves;

(3) Review of helicopter rotor noise mechanisms.

Each of these areas is discussed separately in this report. As most of the results have been published, the research is reviewed in the present final report with emphasis on the most recent results.

2. HIGH SPEED AND SHOCK NOISE

During the initial months of the contract period we completed our basic investigations of the methods of Ffowcs Williams and Hawkings (2) and Farassat (3) for predicting radiated sound due to the motion of solid body volume and surface pressure distributions. We submitted and had published a paper on "The Sound Due to the Acceleration of a Sphere" (4). We obtained excellent agreement between the theory of Farassat and our measurements for this simple case. We concluded that the sound from a solid body at low velocities but high accelerations is well suited to calculation by these methods.

At high advancing blade Mach numbers, helicopter rotor blades generate severe impulsive noise. A substantial portion of this sound has been shown to be due to blade volume and pressure distribution effects. Existing calculation methods are based on the work of Ffowcs Williams and Hawkings and of Farassat. Farassat made numerical calculations on thickness effects at NASA and Pien obtained corresponding results here at Cornell on our previous grant. However, another source of noise is apparently due to the radiation of a shock wave related to the unsteady transonic shock wave on the blade. Such effects have been found in experiments by Tijdemann at NRL in the Netherlands (6) and at AAMRDL by Schmitz, _et al_. (7,8).

Our analysis, most of which has been published in reference 9 analyzes the far field sound due to the formation and disappearance of shock waves on rotors. We first considered the application of the original forms of the solutions derived by Farassat in reference 3 to problems involving unsteady shock waves. These original forms were derived by bringing all of the differentiations in the solution under the integrals. However the resulting forms are complex, difficult to interpret, and required additional near field flow detail. In order to overcome these difficulties in as simple a way as possible and to require a minimum of near field information it is more convenient to leave some of the derivatives outside the integrals while transforming spatial to time derivatives. Farassat (5) has carried out this type of transformation for thickness and force terms and we carried out similar transformations for the Lighthill stress term. Our order of magnitude estimates showed that for impulsively started shocks the Lighthill stress radiation in the forward (flight) direction is dominated by the jumps in properties across the shock. However for finitely varying shock strengths the finite gradients in the flow can also contribute significantly to the sound due to Lighthill stresses.

Our approach was to analyze geometrically simplified models of shocks which are "turned on" and "turned off" to model the appearance and disappearance of transonic flow on advancing rotor blades. Since the actual blade moves subsonically, the near field shock was modelled as a segment of a shock discontinuity surface moving subsonically. We approximated its trajectory as local straight line motion.

Aerodynamic data for shock formation and decay based on work by Caradonna and Philippe (10) and by Murman and Cole (11) were used as the basis of the simplified model of an impulsively started and stopped disc shock. Our results which are given in reference 9, show that the far field sound is an initial sudden expansion followed by a sudden compression. A more realistic slower "turning on" and "off" of the shock would give a smoother sound pulse which will be included in Mr. Kitaplioglu's Ph.D. thesis which is in preparation.

3. BROADBAND ROTOR NOISE SOURCES AND PREDICTION

Helicopters in hover on low speed flight primarily radiate sound due to steady and unsteady rotor blade forces. At frequencies below about 100 Hz the sound is primarily due to constant or azimuthally varying but steady loads. However the more important middle and high frequency part of the noise spectrum is due to higher order loading harmonics which are largely random in nature. As the radiation from known azimuthally periodic loadings has been understood for some time, previous prediction techniques have usually assumed empirical loading laws without dealing with the causes of these loading harmonics. Under our previous grants we showed that much of the previously unexplained noise is due to random loadings from atmospheric turbulence or other inflow disturbances.

However our earlier analyses, although successful, required quite prohibitive numerical computations for sound frequencies above several hundred Hertz. This was because a very large number of radiating modes had to be summed to obtain the Doppler shifted and partly correlated signal at any given frequency and observer location.

Under our present grant we were able to show that the high frequency part of the noise spectra is due to loads which are uncorrelated between blades and which then can be treated in a simplified manner. We were then able to develop a considerably simplified high frequency theory based on a result of Ffowcs Williams and Hawkings (12) for radiation from rotating randomly varying loads. We then devised some approximations to certain integrals appearing in the analysis which made high frequency calculations possible. This new method and some calculated results were reported in reference 13 and are not detailed here. Calculation times with that method ranged from one to forty seconds CPU time per point on an IBM 370-168 for all frequencies below 10,000 Hertz.

In later work which will be presented here and in more detail in Y.N. Kim's Ph.D. thesis and a subsequent publication we devised a further significant simplification of the calculation procedure. The method of reference 13 requires evaluation of an expression of the form

$$\sum_{n_2-\infty}^{n_2+\infty} D_r(|f-n\Omega|)J_n^2\left(\frac{fM_o\cos\phi}{\Omega}\right)$$

where $D_r(f)$ is a complex integral expression for the blade loading spectrum. For large f the number of $D_rJ_n^2$ terms which have to be evaluated becomes very large. For this case we found that for appropriate n_1 we can approximate

$$\sum_{-n_1}^{+n_1} D_r J_n^2 \approx \int_{-n_1}^{+n_1} D_r J_n^2 \, dn$$

and then use the asymptotic result $J_n^2(x) \sim \frac{2}{\pi x} \cos^2(x - \frac{n\pi}{2} - \frac{\pi}{4})$, $(n < x)$ to approximate the average over n at J_n^2 by $\frac{1}{\pi x}$. This technique allowed us to further drastically reduce the number of points needed to approximate $\sum_{-n_1}^{+n_1} D_r J_n^2$. This approximation reduced computation times by a factor of 10 at high frequencies with negligible loss in accuracy, making the new method fully practical for routine use with a variety of loading spectra.

Our research was also concerned with the origins of the random loading spectra causing broadband noise. One important type of blade loading is due to inflow turbulence. A hovering or low flight speed rotor also modifies any ingested turbulence due to the distortion of fluid elements drawn into the rotor plane. This effect can cause large changes in the properties of the turbulence. We presented some preliminary investigations of this effect in reference 13.

Another source of rotor noise is unsteady blade loadings due to downwash fluctuations in blade boundary layers or from other turbulence. Turbulent velocity fluctuations in a boundary layer or separated region are convected at speeds less than free stream velocity and the resulting pressure distributions are somewhat different than those found in classical analyses of convected gusts.

In work in I.C. Theocleous's M.S. thesis the method of Miles (14) was extended to obtain the pressure distributions on flat incompressible inviscid airfoils in a free stream of velocity U and subjected to an upwash field moving with velocity U/λ. In order to determine the character of the pressure distributions associated with turbulent fluctuations the response to gust shapes of the form $\delta(x-Ut/\lambda)$ and $H(x-Ut/\lambda)$ were calculated. The pressure distributions were found using Laplace transform methods from the integral relation between pressure difference and upwash as given by Schwartz or Küssner. For upwash gusts convected at less than free stream speed, as would be the case for boundary layers or separated regions, we find that negative lift peaks occur at the gust front. Conversely for upwash gusts propagating at faster than free stream speed positive lift peaks occur. A typical result is shown in figure 1. Unfortunately the Laplace transform inversion is only asymptotic for certain ranges of time and results for times when the gust is between the midchord and trailing edge can not be computed accurately.

Our most recent work on broadband noise has been on the prediction of rotor noise associated with the so called trailing edge noise mechanism. This work is a part of Y.N. Kim's Ph.D. thesis and will also be written up for journal publication.

We first investigated existing empirical trailing edge noise correlations, most of which were developed for jet flap or for airframe noise configurations. These were unsatisfactory for helicopters as they overpredicted experimental helicopter rotor noise spectra by over 15 dB as we reported in reference 15.

We next investigated theoretical models of existing trailing edge noise and trailing edge loading. Vortex shedding does not appear to be important for full scale rotors and was not investigated. A range of physical models related to trailing edge noise and loading exist and have been analyzed by various authors but they differ with each other on important items such as whether to apply the Kutta condition, and on the locations, convection speeds and types of multipoles used to model the phenomena. A recent critical study by Howe (16) compared many of the conflicting models but it is still not clear which of these models are most realistic. On the other hand Amiet (17,18) analyzed the radiation from a fixed airfoil assuming only that surface pressure spectra are known far from the trailing edge and that the associated velocity field is statistically stationary as it moves past the edge. We used an extension of Amiet's analysis to determine the statistical induced loading at the trailing edge, estimating the effects of spanwise load correlation. We used the measured boundary layer pressure spectra of Willmarth and Roos (19) and our broadband rotor noise calculation techniques to find the results shown in figures 2 and 3. In figure 2 for a rotor at altitude the calculated trailing edge noise is seen to become as important as atmospheric turbulence noise at high frequencies. This is because the small boundary layer eddies are stronger than the eddies of that scale in the ingested atmospheric turbulence. However in figure 3 where the inverted rotor is near the ground the small scale atmospheric turbulence eddies remain stronger over the range of frequencies.

4. REVIEWS OF HELICOPTER AND ROTOR NOISE

As part of our program of identifying the significant noise sources for helicopter rotors an invited review of helicopter external noise was prepared by the principal investigator. Other recent reviews of helicopter noise had been oriented toward various empirically-based prediction methods rather than toward identification of individual source mechanisms and their analytical description. The review prepared under this grant emphasized the physical mechanisms of noise generation and evaluated their importance for helicopters. Potentially important mechanisms which have not yet been sufficiently investigated were identified and the status of prediction capabilities were discussed. This review was published as AIAA Paper 77-1337 and a revised version is scheduled to appear in the AIAA Journal of Aircraft in November, 1978. The required twenty-five reprint copies will be furnished to ARO when they are available.

Also a short review and perspective of rotor noise prediction was prepared for the ARO/NASA/AHS International Specialists Symposium on Helicopter Acoustics, May 22-24, 1978. The review will appear in the published proceedings which will be published shortly.

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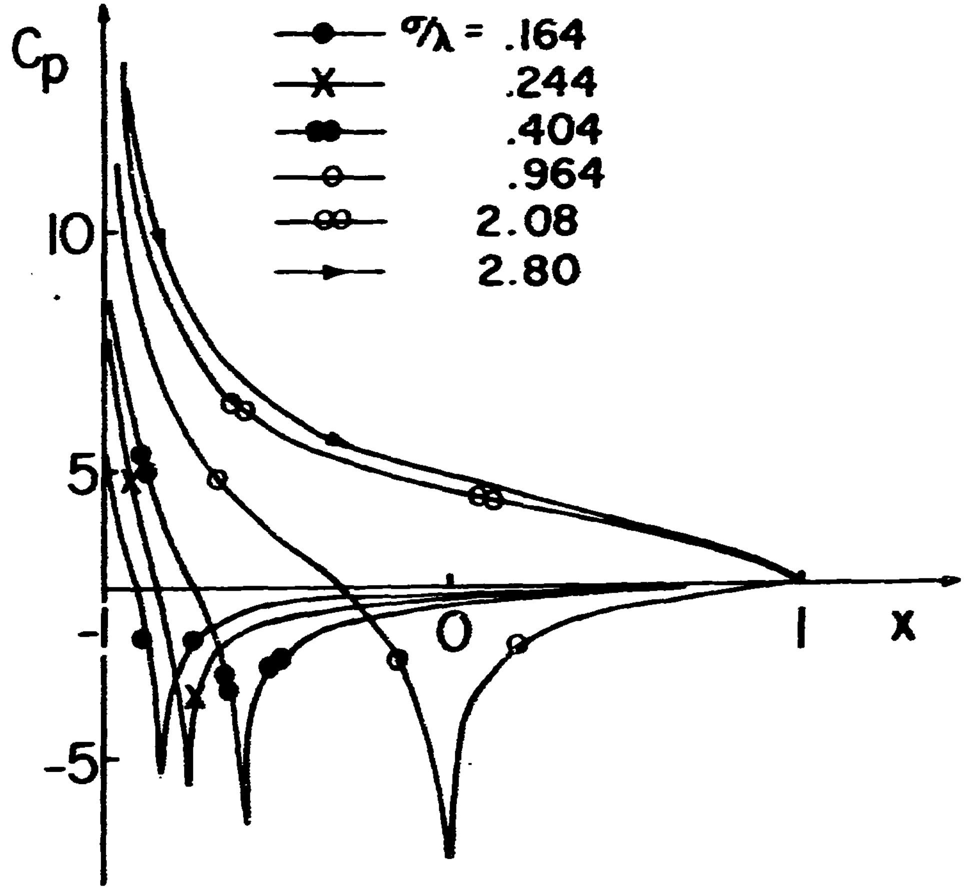

Figure 1. Pressure distribution along airfoil chord for various times for a step function upwash gust travelling at 0.4 free stream velocity. At $\sigma/\lambda = 0$ gust is at leading edge $(x = -1)$; at $\sigma/\lambda = 2$ it is at trailing edge $(x = +1)$.

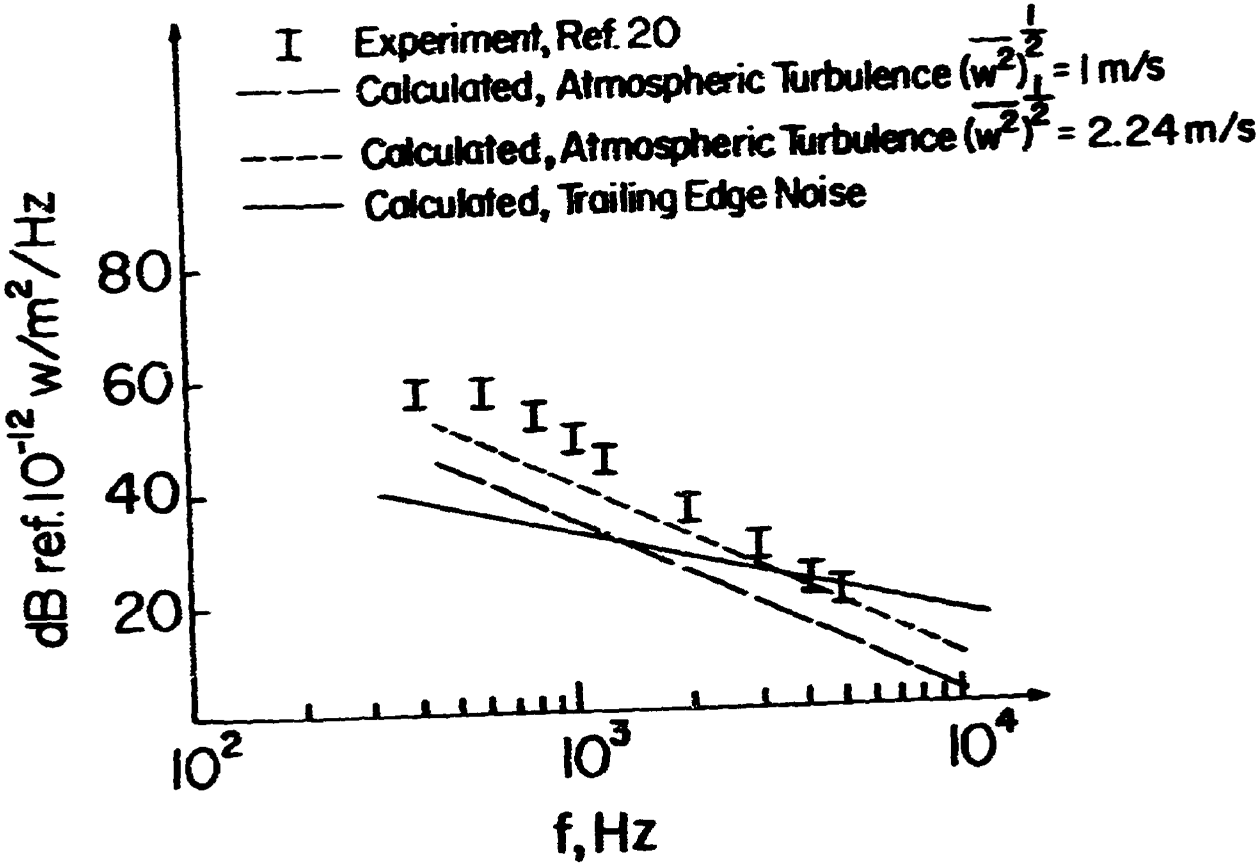

Figure 2. Comparison of atmospheric turbulence noise and trailing edge noise for a helicopter hovering at approximately 100 feet.

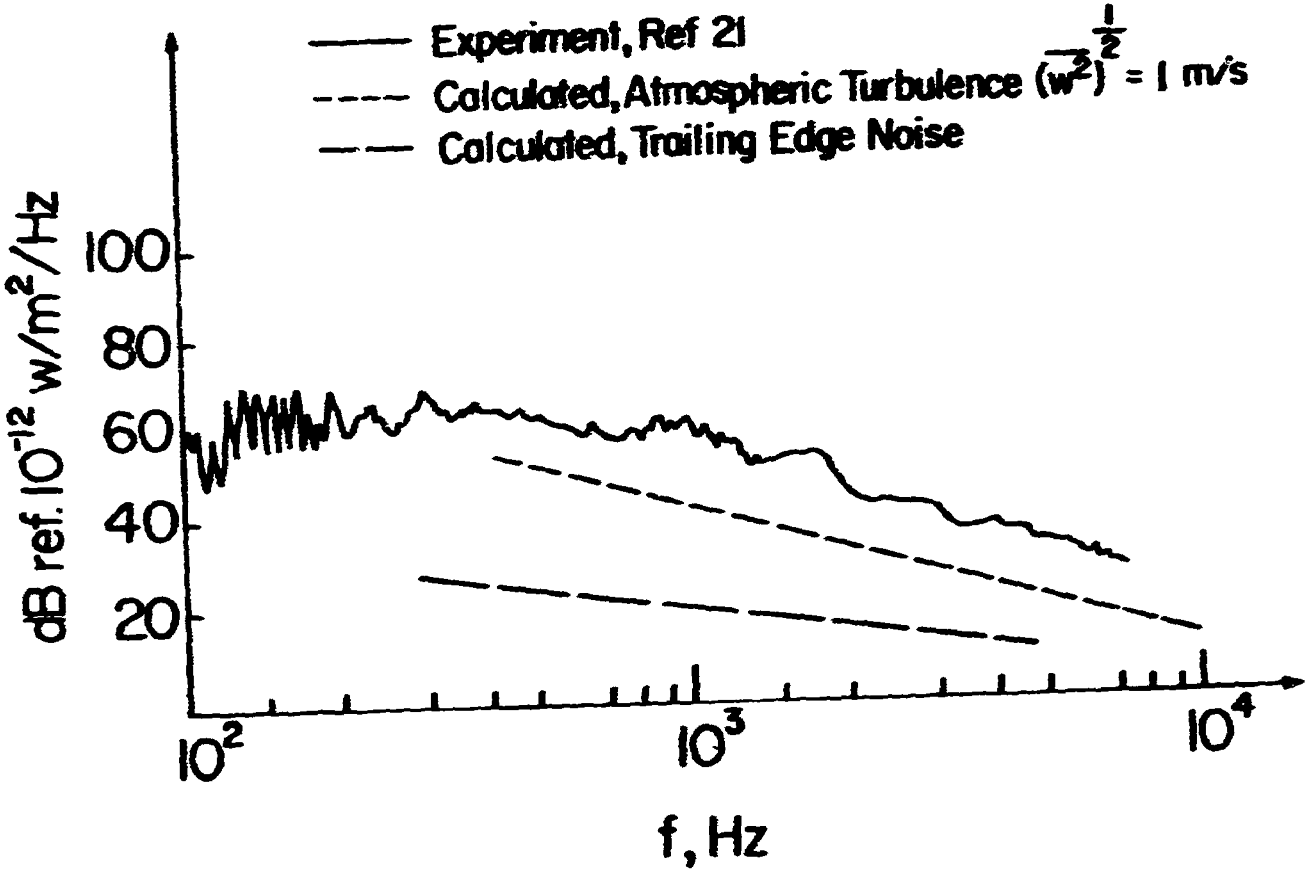

Figure 3. Comparison of atmospheric turbulence noise and trailing edge noise for an inverted rotor near the ground.

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1. Professor A.R. George.
2. Y.N. Kim, Master of Engineering (Aerospace), June 1975
   Ph.D. (expected), January 1979.
3. I.C. Theocleous, M.S., January 1978.
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