Noise Produced by Turbulent Flow into a Propeller or Helicopter Rotor

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Theme

A PROPELLER or helicopter rotor operating in a turbulent atmosphere experiences unsteady blade loading, leading to the production of noise. The noise produced can be broadband, or, if the turbulent eddies are chopped by more than one blade, the noise can be narrow-bank random, i.e., peaked around harmonics of blade passage frequency. This synoptic presents a theoretical analysis of this problem and gives some comparison with experiment and with another theory. A high-frequency assumption is made in the analysis, but indications are that the method is accurate for frequencies above the first few rotor harmonics. Given the spectral characteristics of the turbulence, the analysis is of an absolute nature, containing no adjustable constants, and gives a prediction of both the frequency spectrum and directivity of the far-field noise.

Contents

The frequency content of the noise produced by a dipole moving in a circle and oscillating sinusoidally in strength often is expressed in terms of an infinite series of Bessel functions. This approach was taken by Homicz and George,[1] for example. An alternate approach is to work with the time behavior of the far-field sound rather than the frequency behavior. The expression given by Lowson[2] for the far-field pressure of a force F in accelerative motion is

$$P=\left[\frac{1}{4\pi c_0 r^2 (1-M_n)^2}\,r\cdot\left(\dot{F}+\frac{F}{1-M_n}\dot{M}_n\right)\right] \tag{1}$$

where c_0 is the sound speed, r is the vector from the dipole position to observer, $\dot{M}_n$ is the component of acceleration of the dipole in the direction of the observer, and the brackets imply evaluation at the retarded time.

For a dipole fluctuating in amplitude with frequency ω while moving with angular frequency Ω along a circular path, the $\dot{F}$ term will outweigh the $\dot{M}_n$ term significantly if $\omega >> \Omega$ and M_n is not near 1. With these restrictions, Eq. (1) can be approximated by

$$P=\left[\frac{1}{4\pi c_0 r^2 (1-M_n)^2}\,r\cdot\dot{F}\right] \tag{2}$$

This is, in fact, the same result that would be obtained for a dipole in rectilinear motion. This allows the high-frequency far-field sound to be calculated as if the rotor blade were instantaneously in rectilinear motion. A previous analysis[3] for the sound produced by an airfoil in rectilinear motion than can be applied to calculate the instantaneous sound spectrum produced by the rotor at each azimuthal rotor position, and this instantaneous spectrum can be averaged over the azimuthal rotor position to find an averaged far-field sound spectrum. In taking this average, account must be taken of the different amount of retarded time that the rotor spends at each azimuthal rotor position. Further discussion of this point is given in another paper.[4]

A further factor taken into account in the analysis is the existence of blade-to-blade correlation. If a given turbulent eddy is chopped by more than one rotor blade, the blade-to-blade correlation leads to narrow-band noise peaked around the rotor harmonics. The far-field sound for an airfoil moving in rectilinear motion through a turbulent flow can be expressed in terms of a single wavevector component of the turbulence. The presence of blade-to-blade correlations requires that the single wavevector component be replaced by a summation over several wavevector components. This summation generally is carried out numerically for the calculations presented herein, but, if the frequency of interest is high enough, the summation can be replaced by an integral that can be evaluated in closed form; i.e., the blade-to-blade correlation becomes unimportant, and the result reduces to that for a single blade in rectilinear motion.

The preceding description of the procedure for calculating the far-field sound applies to the sound produced by a spanwise segment of the rotor. This segment must have a spanwise dimension small enough so that the velocity does not vary significantly over the segment but large enough so that the loading correlation from segment to segment is not significant. This latter assumption is consistent with the high-frequency assumption mentioned previously, since high frequency corresponds to small correlation length. Thus, to find the noise contributed by the entire rotor, an integral over span must be performed.

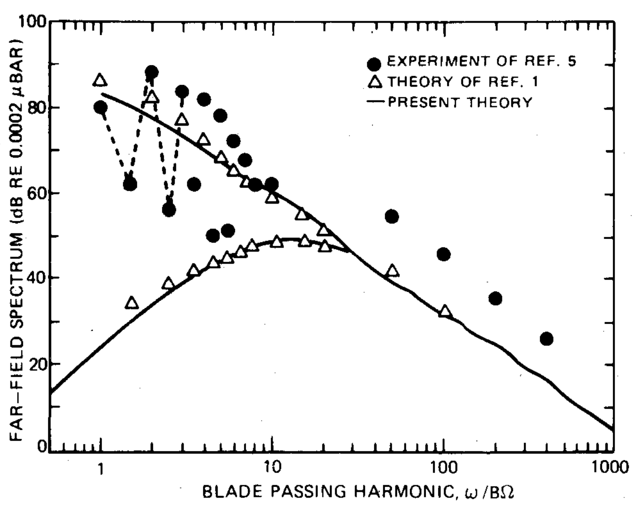

Fig. 1 Far-field sound spectrum compared with experiment and previous theory.

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The far-field noise also depends on the airfoil response function. At the higher frequencies such that the acoustic wavelength is smaller than the airfoil chord, noncompactness of the airfoil loading distribution must be included in the analysis. Closed-form expressions for the airfoil response function are given in Ref. 4 for two regimes: 1) the long acoustic wavelength regime, and 2) the short acoustic wavelength regime. These expressions agree to within a few percent of numerical solutions for the problem of a flat-plate airfoil interacting with a gust in compressible flow. From these expressions, the pressure distribution on a flat-plate airfoil encountering a skewed sinusoidal gust in compressible flow can be determined with good accuracy. Quite good agreement between experiment and theory has been obtained for the sound spectrum produced by an airfoil in rectilinear motion through a turbulent flow[3] using these response functions.

The spectrum of the turbulence flowing into the rotor plane also must be specified. The most appropriate expression for this spectrum is not known at this time. Even if the properties of the atmospheric turbulence were known, these properties presumably would be distorted as the turbulence is accelerated into the rotor plane. Because of this uncertainity, the calculations presented herein assume an isotropic homogeneous turbulence model; in particular, the von Karman spectrum model is used. This model gives a k^4 behavior for small k and a $k^{-5/3}$ behavior for large k, where k is the wave-vector amplitude.

The numerical results presented in Figs. 1 and 2 were calculated by computer. The computer carries out a summation over the turbulence spectrum because of the blade-to-blade correlation mentioned previously. Also, the spectrum was averaged over azimuthal position; it was found that summing over eight azimuthal positions (effectively 16 because of the symmetry of the problem) was sufficient to give good accuracy. In addition, an integration over the blade span can be performed as mentioned before, but the calculations presented here use an effective radius instead. The resulting computer program takes very little time to execute, generally less than 1 sec/point, significantly improving on the time needed to execute the program of Ref. 1. The results of the calculations are shown in Figs. 1 and 2. Figure 1 shows a spectrum calculation compared with the theory of Homicz and George[1] and the experiment of Evans and Nettles.[5,6] Because the turbulence properties were not measured in Ref. 5, homogeneous isotropic turbulence was assumed with the same length scale and intensity as in Ref. 1. The parameters chosen for the calculations are blade number = 2, rotor rotational frequency = 5.4 Hz, far-field distance = 66.6 m, chord = 0.533 m, axial Mach number = 0.027, sound speed = 330 m/sec, turbulence intensity = 1 m/sec, turbulence integral scale = 27.5 m, blade span = 6.66 m, effective blade span = 6.33 m, effective source radius = 5.33 m, and the observer is assumed to be at an angle of 117° from the overhead on-axis position. These were the values chosen by Homicz and George,[1] and they also correspond closely with the values for the experiment of Evans and Nettles[5,6]

In Fig. 1, the agreement between the present theory and experiment is only fair, but this is not surprising considering the fact that the turbulence length scale and intensity were not measured in the experiment. The agreement between the present theory and that of Homicz and George is quite good, however. Reference 1 uses a more approximate airfoil response function but does not make the high-frequency assumption of the present analysis. The close agreement between the two theories for frequencies above the first few harmonics, however, shows that this assumption is not as restrictive as it might seem at first.

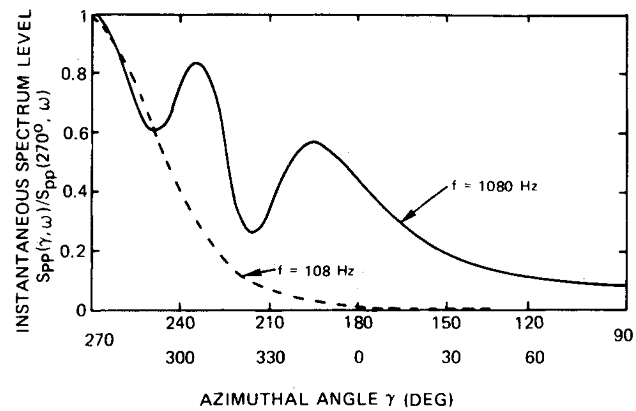

Fig. 2 Instantaneous spectrum as a function of azimuthal rotor position.

The convective amplification factor is evident in Fig. 2, which shows the instantaneous spectrum level as a function of rotor azimuthal position before averaging over azimuthal angle. For 270°, the rotor is moving toward the observer and the noise spectrum reaches a maximum for both frequencies shown, whereas for 90° the spectrum is a minimum because the rotor is moving away from the observer. The oscillations in the 1080-Hz curve are due to the oscillatory behavior of the Fresnel integrals, which occur in the airfoil response function for large frequency.

References

[1]Homicz, G. F. and George, A. R., "Broadband and Discrete Frequency Radiation from Subsonic Rotors," *Journal of Sound and Vibration*, Vol. 36, Sept. 1974, pp. 151-177.

[2]Lowson, M. V., "The Sound Field for Singularities in Motion," *Proceedings of the Royal Society* (*London*), Vol. A286, Aug. 1965, pp. 559-572.

[3]Paterson, R. W. and Amiet, R. K., "Acoustic Radiation and Surface Pressure Characteristics of an Airfoil Due to Incident Turbulence," AIAA Paper 76-571, July 1976; also *Journal of Aircraft*, to be published.

[4]Amiet, R. K., "Noise Produced by Turbulent Flow Into a Propeller or Helicopter Rotor," AIAA Paper 76-560, Palo Alto, Calif., 1976.

[5]Evans, T.D. and Nettles, W.E., "Flight Test Noise Measurements of a UH-1B Helicopter," paper presented at the AHS/UTA Joint Symposium on Environmental Effects on VSTOL Designs, Arlington, Texas, November 1970.

[6]Johnson, H. K. and Katz, W. M., "Investigation of the Vortex Noise Produced by a Helicopter Rotor," U. S. Army Aviation Military Research and Development Lab., Moffett Field, Calif., TR 72-2, 1972.