NOISE GENERATION OF UPWIND ROTOR WIND TURBINE GENERATORS

R. H. Spencer

The Boeing Vertol Company
P.O. Box 16858
Philadelphia, PA 19142

ABSTRACT

Noise sources of wind turbines with rotors upstream of the support structure are discussed along with methodology for sound level prediction. Estimated noise levels for the MOD-2 wind turbine are presented operating in both the upwind and downwind configurations. Results indicate that upwind rotor configurations may be advantageous from an acoustical standpoint.

INTRODUCTION

Wind turbine installations in the past generally have had low acoustic signatures that ranged from unobtrusive to those which generated some annoyance in the immediate vicinity of the turbine while not dominating the ambient signature of the surrounding area. With the operation of the MOD-1 system, however, a more active interest in the noise of wind turbines took place. The acoustic signature of this rotor surprised engineers involved with the program as well as those who became associated as a direct result of the operation of the MOD-1 system. The predominant source of noise for this downwind rotor configuration appears now to be fluctuating airloads arising from interaction of the rotor and the wake trailed by the tower support structure. Upwind rotor configurations do not experience the same magnitude of airload fluctuations as the blade passes upstream of the tower, and other noise sources dominate. The subject paper discusses sources of noise on upwind rotor configurations and, in particular, the Boeing MOD-2 system.

SOURCES OF NOISE

Wind turbine generator systems may be classified into two categories with respect to the position of the rotor relative to its support tower structure: (1) rotors which operate upwind and (2) those which operate downwind of the support structure. Rotors which are positioned closely downstream of the tower experience airload fluctuations as the blades pass through the disturbed wake of the structural members. Noise sources for wind turbines consist of rotor periodic and non-periodic components as well as those due to mechanical, hydraulic and electrical components housed within the hub, although these latter sources are negligible beyond a few rotor diameters. Figure 1 presents the components of rotor noise classified with respect to their time domain characteristics. The periodic elements consist of thrust, drag and radial forces on the blade which arise from the steady and fluctuation airloads, wind shear effects, and periodic airload disturbances resulting from the tower wake on a downwind rotor, the aerodynamic reflection of the tower on an upwind rotor, or possible interactions with the trailed vortex system.

Nonperiodic components of rotor noise consist of (1) random load fluctuations resulting from atmospheric turbulence ingested into the rotor, and (2) the shear stress effects of a viscous medium. Noise arising from rotating blades ingesting disturbances in the flow has been investigated previously by researchers interested in the effects of axial flow fans[1,2,3]. More recently, atmospheric turbulence effects on propellers and helicopter rotors were studied, among others, by Hanson[4], George and Kim[5] and Humbad and Harris[6]. This research showed that

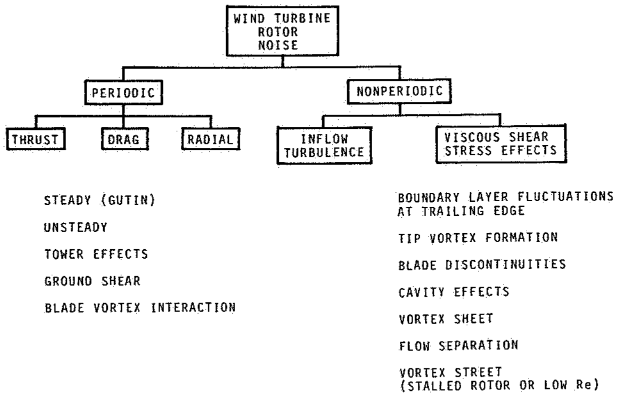

Figure 1 - Wind turbine generator noise sources

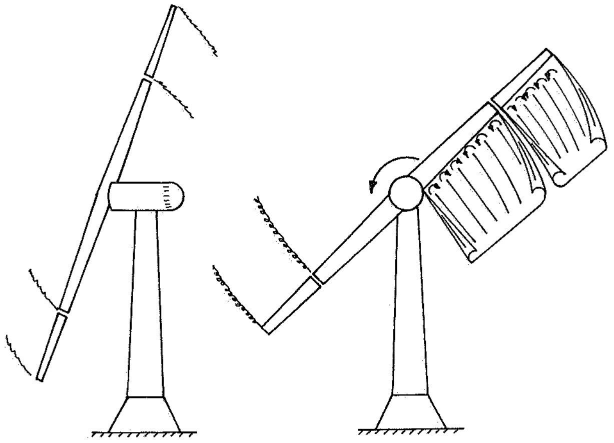

Figure 2 - Trailing vortex sheet and filaments

sources which can arise from shear stresses in the viscous medium are (1) turbulent boundary layer noise, (2) trailing edge noise resulting from unsteady flow, (3) noise of trailed vortex filaments on the tip and other blade discontinuities, such as the joint of a segmented rotor, and (4) the trailed vortex sheet arising from the spanwise loading gradient, as well as loading fluctuations at each blade station which gives rise to a sheet of vortex filaments shed along the blade span. This vortex sheet rolls up within a few chord lengths into the trailed filaments at the tip and into a weaker system at the root. The blade discontinuity of a segmented rotor gives rise to an additional filament (Figure 2).

In a recent paper presented at the HAA/NASA Advanced Rotorcraft Technology Workshop[7] Raney, Hood and Biggers compared the contribution of the unsteady nonperiodic sources. This is reproduced here as Figure 3 and shows that turbulence ingestion appears harmonic in content, but in reality is random atmospheric turbulence modulated at blade passage frequency.

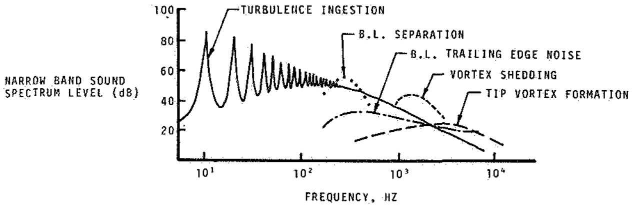

Figure 3 - Noise from unsteady loading sources

NOISE PREDICTION METHODOLOGY

The method of Lowson and Ollerhead[8] was used to determine the periodic forces on the rotating blade. Harmonic amplitudes of rotational noise can be determined from

$$C_n = \sum_{\lambda=0}^{\infty} k \cdot \frac{T}{R.r\ \lambda} \left\{ nM\sin C_{\lambda_T} J_1' - C_{\lambda_D} J_2' + (nM\cos\theta C_{\lambda_C}) J_3' \right\} \quad (1)$$

Two methods were evaluated to account for tower wake effects. The first was Lowson's noncompact source theory, Eq. 2, which may be used to predict periodic components of rotational noise if spanwise and azimuthal distribution of airloads and velocity are known.

$$P = \frac{1}{4\pi a_0^2} \int \left[\frac{x_i - y_i}{a_0 r(1-M_r)} \frac{\partial}{\partial t} \left(\frac{F_i}{r(1-M_r)} \right) \right] d\underset{\sim}{\eta} \quad (2)$$

Airloading near the tower structure was modified by wake velocity and incidence effects. This procedure showed that using 11 spanwise airloading stations and 180 azimuthal stations, harmonics of rotor noise up to approximately 40 could be determined. An alternate method of including wake effects was investigated in an attempt to improve the higher harmonic prediction. Wright[9] expanded Lowson's theory to include the response to a vortex. In the form written by Pegg[10], the expression is,

$$P_{mB} = \frac{\Delta L}{L_0} E \rho_W K_T mB \frac{\sin\pi(ft_0-1)}{4(ft_0-1)} - \frac{\sin\pi(ft_0+1)}{4(ft_0+1)} \quad (3)$$

This was evaluated for the MOD-1 turbine using the wake structure downstream of the tower as measured by Savino[11] on a wind tunnel model. These results, shown in Figure 4, indicate reasonable agreement with measured data at 35 and 23 RPM. Prediction of harmonic components of rotor noise are reliable provided airloads and wake structure are known.

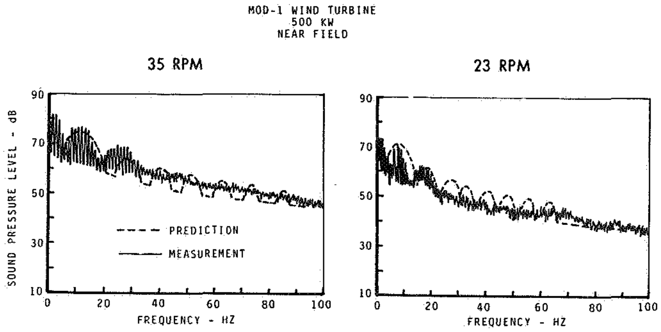

Figure 4 - Comparison of measured and predicted MOD-1 noise levels

Prediction of the nonperiodic sources of rotor noise on the other hand is less exact. For example, the spectrum, scale length and intensity of random atmospheric turbulence is not known nor have pressure fluctuations in the boundary layer been thoroughly documented. Detailed knowledge of the structure of the wake of the rotor is required to estimate tip vortex noise and trailing edge noise and this information is not available. As a result, estimation of the noise due to viscous shear effects has been predominantly empirical. Airframe noise prediction procedures are currently empirically based in that analytic methods have not been adequately correlated with data. Fink[12], for example, describes the noise of fixed wind aircraft airframes, leading edge devices, trailing edge flaps and landing gear by empirical trends.

Since the noise due to nonperiodic sources results from viscous effects rather than from turbulent inflow, the noise signature can be related to profile drag of the rotor. Trends developed by Boeing Vertol during the Heavy Lift Helicopter program showed that broadband noise above 300 Hz was related to rotor profile power by

$$SPL_{2KHz} = 20 \text{ Log } p - 10 \text{ Log } \frac{A_b}{\cos^2\gamma + 0.1} + K + 20 \text{ Log } \frac{110}{r} \quad (4)$$

Broadband noise profile power trends based on a helicopter rotor are shown in Figure 5. The K term derived for helicopter rotors (-3 to -13) appears to be too large for wind turbines and preliminary data from the MOD-0 unit indicates that a K of -26 gives good agreement. There is some indication that for a given profile power, increased blade area, A_b, reduces broadband noise. This would indicate that reduced turbulence intensity on and in the wake of the blade reduces the nonperiodic noise. Directivity is accounted for in the angle between the thrust line and the observer, γ, and distance effects in the last term. A spectum slope of 6db per octave appears to give good agreement for segmented rotors.

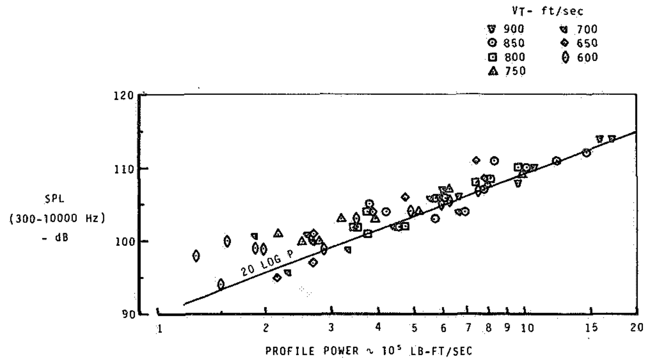

Figure 5 - Broadband noise profile power trends

PREDICTION OF MOD-2 NOISE

Noise levels of the MOD-2 turbine were estimated (Figure 6) using the methods of the previous section including Wright's theory for the tower wake response. As an upwind system, the velocity profile of the tower reflection shown in Figure 7 was included. This profile was developed using theory[13] for flow around circular cylinders as well as measured profiles behind model towers. Ground shear was considered to be insignificant and was not included in the airloading. Broadband noise was determined using Equation 4. Note that broadband noise for MOD-2 establishes

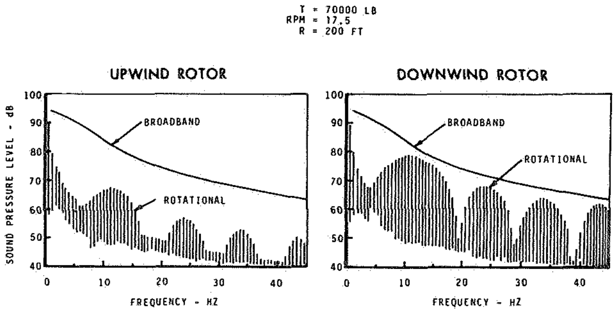

Figure 6 - Predicted MOD-2 noise levels

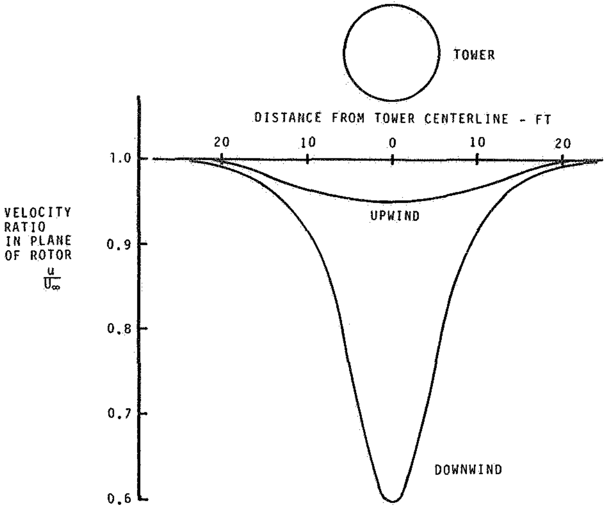

Figure 7 - Wind velocity profile used in analysis

the signature, while for MOD-1 (Figure 4) harmonic levels dominate. Broadband levels also dominate the MOD-0 rotors.

An estimate of the rotational noise of the MOD-2 turbine was made assuming it was operating as a downwind rotor. In this case, the downwind velocity profile of Figure 7 was used. The marked increase in higher harmonic sound level illustrates the benefit which results from rotors that operate in undisturbed air.

CONCLUSIONS AND RECOMMENDATIONS

Upwind rotor wind turbines, which produce only nonperiodic sources of noise such as generated by random atmospheric turbulence, a turbulent boundary layer or the formation of a trailed tip vortex filament result in a nonimpulsive acoustic signature that is characterized by a swishing, rather than a thumping sound. These sources of noise tend to have low radiation efficiencies and broadband spectra which are more acceptable than discrete tonal noise components. Any device which reduces the disturbed wake behind the tower structure of a downwind rotor will also improve the acoustical signature of a downwind rotor.

Upwind rotors appear to have an advantage over downwind rotors from an acoustical standpoint. Predictions for the MOD-2 turbine indicate that the noise signature will be of a broadband nature. Although noise measurements have not been made on the MOD-2 turbine to date, comments from observers indicate that the predominant noise is a swishing sound characteristics of a broadband noise source. Levels between 60-65 dBA have been predicted for MOD-2 at a distance of 200 ft, similar to those near a freeway with moderate traffic at an equivalent distance.

Improved prediction methods for broadband, nonperiodic sources of noise are required in order to estimate the acoustic signature of new turbine generators with confidence. The existing empirical broadband methodology lacks a rigorous analytical understanding which must be developed from an adequate data base in order to accurately quantify these sources. Additional measurements should be made to verify the unsteady loading noise theory as it is developed.

ACKNOWLEDGEMENT

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NOMENCLATURE

A_b	total blade area
c	speed of sound
C_n	amplitude of nth harmonic at specified field point
$C_{\lambda T}$, $C_{\lambda D}$, $C_{\lambda C}$	thrust, drag and radial force harmonic coefficient
E	number of interactions per revolution
F_i	aerodynamic force components
J_i	complex collection of Bessel functions of argument ($nM\cos\theta$)
k	airload decay constant
K	constant, nonperiodic equation
K_T	thrust constant
$\frac{\Delta L}{L_o}$	fractional steady load change per blade
M	rotational Mach number
M_s	source Mach number in direction of observer
$n = MB$	harmonic number x number of blades
P	rotor profile power
$p(t)$	instantaneous near-field acoustic pressure
r	distance between rotor center and field point
R	radius of action of blade forces
s	blade loading harmonic number
S	distance between source and observer
T	thrust
x_i	observer coordinates
y_i	source coordinates
θ	angle between disc plane and field point
γ	angle between thrust axis and field point
λ	air loading harmonic number
ρw	load solidity (fraction of the effective disc annulus occupied by the unsteady loading region
χs	blade loading spectrum function

QUESTIONS AND ANSWERS

R.H. Spencer

From: G. Greene

Q: Did you identify any source for MOD-2 which would not also be present in a downwind machine?

A: *No. It appears that the broadband sources are present on upwind and downwind rotors. On downwind rotor wind turbines, the periodic components dominate the acoustic spectrum--at least at frequencies below 200-300 Hz.*