PREDICTIONS OF LOW-FREQUENCY AND IMPULSIVE SOUND RADIATION FROM HORIZONTAL-AXIS WIND TURBINES

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ABSTRACT

This paper develops theoretical models to predict the radiation of low-frequency and impulsive sound from horizontal-axis wind turbines due to three sources: (1) steady blade loads; (2) unsteady blade loads due to operation in a ground shear; (3) unsteady loads felt by the blades as they cross the tower wake. These models are then used to predict the acoustic output of MOD-I, the large wind turbine operated near Boone, N.C. Predicted acoustic time signals are compared to those actually measured near MOD-I; good agreement is obtained.

INTRODUCTION

The possibility of satisfying some fraction of our energy needs with wind power has recently received serious consideration. As a result, a number of experimental vertical- and horizontal-axis wind turbines have been constructed under DOE sponsorship and are presently being tested. In this paper we present aerodynamic and acoustic models developed or adapted to predict sound radiation from horizontal-axis wind turbines due to the following three acoustic sources: (1) steady blade loads, (2) unsteady blade loads due to wind shear, and (3) unsteady loads acting on the blades as the latter pass through the tower wake.

Below, we describe the mathematical models used to predict noise due to these sources and apply these models to calculate the acoustic output of the DOE/NASA MOD-I wind turbine (for which some tower wake data and sound measurements are available) under typical operating conditions: a free stream of 35 MPH and rotor speeds of 23 and 35 RPM. Although possibly an important cause of impulsive low-frequency sound radiation under certain operating conditions, cross flow into the rotor was not studied here due to difficulties in aerodynamic modeling similar to those met in non-rigid wake analyses for helicopter rotors (ref. 1). Study of this mechanism should be part of future theoretical and experimental research on wind turbine noise. In the present preliminary study we are mainly concerned with modeling the rotor aerodynamics in order to determine the strength and frequency content of sources of sound on the rotor disk; we do not consider terrain and atmospheric effects on the propagation of such sound once it has been created. So, the models developed here for mechanisms (1)-(3), above, do not take into account the presence of the ground plane or the effects which the wind profile or an atmospheric temperature gradient will have on acoustic propagation.

The acoustic models used to predict sound due to (1), steady blade forces and (2), unsteady blade forces to ground shear are based on, respectively: the classical Gutin propeller noise theory (ref. 2); and its generalization for the case of unsteady blade sources (ref. 3). In both studies we used lifting-line theory coupled with a vortex-lattice-wake model to calculate loads at chosen radial stations for each blade. The wake was assumed to be semi-rigid in that it was allowed to move with the local wind velocity (ref. 4). We did not assume compactness of acoustic sources on the rotor disk which would have simplified the analysis somewhat.

To investigate the acoustic effect of (3), blades cutting through the tower wake, we applied the blade-slap theory of ref. 5. Here. the unsteady airloads acting on a blade passing through the mean profile of the tower wake were obtained using Filotas' linear, unsteady aerodynamic theory (ref. 6). The wake data used in the calculations is that given in ref. 7 for a 1/40th-scale model of MOD-I. Predictions of sound are in good agreement, both quantitatively and qualitatively, with field measurements.

FORMULATION

A. Sound due to Steady Blade Loads (Gutin noise)

Even if the tower and rotor wakes did not interact with the turbine blades, and ground shear and cross flows were absent, sound would radiate from a wind turbine due to the rotary motion of steady blade loads. The model used here to study the contribution of this source mechanism to the total far-field signal is based on an adaptation of the classical Gutin propeller noise theory (ref. 2); propagation of sound was assumed to take place in a stationary medium and the acoustic effect of the presence of a ground plane was neglected. The source representation for each blade did not take advantage of acoustic compactness in either the chordwise or radial directions. Instead, we constructed a distributed source region for the rotor plane (zero coning angle) by using values of blade thrust and in-plane forces for six radial stations. Furthermore, at each station these values of force were distributed along the local chord assuming a flat-plate loading distribution.

The actual calculations of blade forces were performed using the lifting-line aerodynamic numerical model described in detail in ref. 4. The model uses curved grids or lattices of trailing and shed vortices to represent the wake behind a turbine rotor in a nonuniform incident free stream. Each lattice has its origin at the trailing edge of a rotor blade and is allowed to change shape as each of its grid points is convected with the local value of the nonuniform free stream velocity; such a wake is "semi-rigid" in current aerodynamic terminology. The blade loads are calculated using an iterative procedure. The code, named US-21 by its original developers (ref. 4), outputs values of blade forces around the rotor for an input ground shear; it can calculate steady blade loads for the special case of a uniform rotor inflow. Although based on potential theory, US-21 incorporates some viscous effects in the aeroacoustic model by computing values of local skin-friction drag from knowledge of the calculated potential flow field and the drag coefficients for each local blade section. Figure 1 shows the coordinate system used in the acoustic model for the steady loads; since the Gutin sound field is axisymmetric, only the angle ψ is needed to describe the predicted directivity patterns.

In the classical theory of Gutin noise (ref. 2) the pressure level P_s at the s^{th} harmonic of the blade-passage frequency is given by the following expression:

$$P_s(r,\psi) = -\frac{i}{2r} e^{\frac{isB\Omega r}{c_o}} (-i)^{sB} \left\{ \frac{sB\Omega \cos\psi}{c_o} \int_0^R dr' r' T(r') \cdot A_s(r') J_{sB}\left(\frac{sB\Omega r' \sin\psi}{c_o}\right) + sB \int_0^R dr'\, I(r') A_s(r') J_{sB} \cdot \left(\frac{sB\Omega r' \sin\psi}{c_o}\right) \right\} \tag{1}$$

where r,ψ define the observer's position in the axisymmetric (in γ) Gutin sound field; B stands for the number of blades, c_o for the speed of sound, and Ω and R for the rotor's speed and radius, respectively. $T(r')$ and $I(r')$ denote the values in pounds per linear foot of steady thrust and in-plane forces, respectively, computed by US-21 at six radial stations for each blade; r' is the distance separating each station from the hub. We chose stations located at 20, 30, 40, 60, 75, 85, and 95% of the rotor radius. At each, we distributed the values of the calculated forces along the local chord $c(r')$ using a flat-plate loading shape $\Delta p \sim \sqrt{(x+x_{te})/(x-x_{Le})}$; the Fourier coefficients of the load shape functions are designated $A_s(r')$ in (1). With $\gamma_o(r')$ indicating the position of the trailing edge of each blade section for each radial station relative to that of $r' = 0.2\,R$, we have, for the thrusts (the in-plane forces were treated similarly)

$$\Delta p(r',\gamma) = \begin{cases} \dfrac{T(r')}{\pi c(r')/2} \sqrt{\dfrac{\gamma-\gamma_o(r')}{\gamma-\gamma_o(r')-c(r')/r'}} & \text{for } \gamma_o(r') < \gamma < \gamma_o(r') + \dfrac{c(r')}{r'} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

and so, by Fourier's theorem,

$$\Delta p(r',\gamma,t) = T(r') \sum_{s=-\infty}^{\infty} A_s(r') \exp[2\pi i s(\gamma-\Omega t)/\Gamma] \tag{3}$$

Here Γ is $2\pi/B$; for the two-bladed MOD-I, $\Gamma = \pi$.

Having calculated the harmonics by means of (1), we obtain the acoustic signal p using

$$p(r,\psi,t) = \sum_{s=-\infty}^{\infty} P_s(r,\psi) e^{-isB\Omega t} \tag{4}$$

where t is time.

A Fast-Fourier Transform routine calculated the $A_s(r')$ coefficients in (3) and the time signal from (4). A sample size of 2048 points was used to represent the load-shape functions for every radial station. The same number was used to obtain the time signal from the calculated harmonics.

B. Low-Frequency Sound due to Operation in a Ground Shear

Since the turbine operates in the earth's boundary layer, the actual free stream can be far from uniform and the associated acoustic field far from axisymmetric. Low-frequency sound then has two origins: (1) the steady loads in rotary motion, as for uniform flow; and (2) the unsteadiness due to the variation of blade forces around the rotor.

As in the Gutin noise study, the acoustic model we used to investigate the effect of wind shear does not take advantage of compactness of acoustic sources on the rotor. The distributed source representation was constructed as previously described, that is, blade loads (thrust and in-plane) were calculated at six radial stations and at each such station their local values were distributed across the local chord using the flat-plate loading shape. The acoustic theory used is the standard generalization of the Gutin model to allow blade forces to vary around the rotor (ref. 3). We assumed that sound propagates in an infinite stationary medium with no ground plane. Program US-21 calculated the blade loads for the turbine operating cases of interest.

We considered an example of a free stream with a shear linear in profile constructed from the sum of a uniform 35 MPH free stream and a linear function with a magnitude of 8 MPH at the highest and lowest points on the rotor. Such a model for shear, besides approximating well most free-stream profiles, enabled us to compare the predicted acoustic fields to those obtained here using Gutin's theory because, for the small blade-pitch cases considered here, the pressure far field for linear ground shear contains approximately the same amount of Gutin noise as its uniform-flow counterpart. This allowed us to isolate the acoustic effect of unsteadiness due to the nonuniformity of the incident rotor inflow.

The standard generalization of Gutin's theory for nonuniform incident inflows contains the following expression for the harmonics of the acoustic signal in the far field (ref. 3):

$$P_s(r,\gamma,\psi) = -\frac{i}{2r} e^{\frac{isB\Omega r}{c_o}+isB\gamma} \sum_{q=-\infty}^{\infty} \left\{ (-i)^{(sB+q)} \left[\frac{sB\Omega\cos\psi}{c_o} \int_0^R dr' r' B_q^T(r') A_s(r') J_{sB+q}\left(\frac{sB\Omega r'\sin\psi}{c_o}\right) + (sB+q) \int_0^R dr' B_q^I(r') A_s(r') J_{sB+q}\left(\frac{sB\Omega r'\sin\psi}{c_o}\right) \right] \right\} e^{\frac{2\pi i q\gamma}{\Gamma'}} \tag{5}$$

where, since the flow into the rotor is not uniform, the thrust and in-plane forces T and I become functions also of γ, the in-plane rotor angle. We then write, for the thrust,

$$\Delta p(r',\gamma)=\begin{cases}\dfrac{T(r',\gamma)}{\pi c(r')/2}\sqrt{\dfrac{\gamma-\gamma_o(r')}{\gamma-\gamma_o(r')-c(r')/r'}} \\ \quad \text{for } \gamma_o(r')<\gamma<\gamma_o(r')+\dfrac{c(r')}{r'} \\ 0 \\ \quad \text{or otherwise}\end{cases} \tag{6}$$

so that in place of (3) we now have

$$\Delta p(r',\gamma,t)=\sum_{q=-\infty}^{\infty} B_q^T(r')e^{\frac{2\pi i\gamma q}{\Gamma'}}\sum_{s=-\infty}^{\infty} A_s(r')$$

$$\cdot\exp[2\pi isB(\gamma-\Omega t)/\Gamma] \tag{7}$$

where the substitution $T(r',\gamma)=\sum_{q=-\infty}^{\infty} B_q^T(r')e^{\frac{2\pi iq\gamma}{\Gamma'}}$ has been made. Here, $\Gamma'=2\pi$, and the $B_q^T(r')$'s are the Fourier coefficients of $T(r',\gamma)$, calculated numerically for each radial station using a Fast-Fourier Transform routine. Equations similar to (6) and (7) were also used to express the in-plane forces $I(r',\gamma)$. $T(r',\gamma)$ and $I(r',\gamma)$ changed around the rotor only very gradually for the case of linear shear studied here; so we found that they and their transforms could be adequately represented by 24 sample points.

The time signal is still given by eq. (4).

C. Impulsive Sound due to the Passage of the Blades through the Tower Wake

In order to investigate sound radiation due to the tower wake we applied a modification of the helicopter-blade slap theory of ref. 5. Briefly, the present model performs the following sequence of calculations: (1) the measured mean tower-wake velocity profile is expressed as a sum of upwash gusts by the Fourier transform theorem; (2) the unsteady force acting on a blade passing through a single gust is determined using Filotas' aerodynamic theory; (3) the unsteady force acting on a blade as it encounters the tower wake is obtained by superposition of solutions from (2); (4) spanwise superposition of solutions of (3) is applied to model the three-dimensional effects of blade rotation and finiteness in span; (5) the wave equation in an infinite stationary medium (with no ground plane) is solved with the aerodynamic forces as boundary condition.

In step (1) above, we used the wake profile approximately at the 74% rotor radius station to represent the profiles at all radial positions. The actual tower wake data for the numerical calculations was taken from ref. 7, where the 74% radial position corresponds to a height of 23.2" from the base of a 1/40th-scale model of MOD-I. The mean wake velocity measurements were made at points downstream of the rotor which were at a distance from the tower-center line of 13.13" (43.77 feet in scale); we assumed these did not differ greatly from those on the actual rotor plane, which for the model is at a distance of 9.10" (or 30.33 feet in scale) from the tower-center line. Two sets of calculations were performed, one using a rotational speed of 35 RPM and the other 23 RPM. In each we investigated wakes for free streams oriented at 0°, 20°, and 45° with respect to the tower structure; for convenience, computer generated reconstructions of these velocity profiles normalized by the free stream are presented in figs. 2a-c. In each, the abscissa, which represents the distance across the tower wake normal to both the tower and the free stream, has been scaled to actual MOD-I dimensions.

To calculate the local unsteady load acting on a blade section passing through the tower wake, we use Filotas' linear two-dimensional aerodynamic theory (ref. 6). The model is adapted from ref. 5, where it was used to predict noise due to blade-vortex interaction in helicopter rotors. Its application here is justified by the following two conditions on turbine operation and tower wake characteristic, respectively, which generally are met by wind turbines: (1) small advance ratio (small ratio of rotor inflow velocity to rotor tip speed); and (2) small sector of rotor azimuth occupied by the tower wake.

We assumed the wake was two-dimensional, that is, that the same wake profile existed at all positions along the tower height. Also, we used a local two-dimensional model for the blade unsteady aerodynamics. Later, we incorporated some three-dimensional effects of blade rotation and finiteness of blade length into both aerodynamic and acoustic models.

Let $w(y)$ denote the upwash felt by a blade passing through the tower wake; the variable y measures the distance normal to the radial direction on the rotor plane. By Fourier's theorem, we express $w(y)$ as a sum of sinusoidal gusts of varying amplitude $W(s)$

$$w(y) = \int_{-\infty}^{\infty} ds\, W(s)\, e^{isy} \tag{8}$$

The unsteady load $\bar{L}(t,s)$ acting on the blade due to the interaction with a single gust is obtained applying Filotas' aerodynamic theory:

$$\bar{L}(t,s)=\left[\frac{\pi\rho(\Omega R)^2}{\sqrt{1+2\pi s}}\, c\exp\left(1-\pi^2/(2+4\pi s)\right)\right] W(s)e^{-ist} \tag{9}$$

where ρ is the background air density, Ω and R the rotor speed and rotor radius, respectively, and c the blade chord. We shall refer to the term in brackets in (9) as $L_o(s)$. From (9), and using superposition, we obtain the unsteady blade loading

$L(t)$ due to the passage through the tower wake

$$L(t) = \int_{-\infty}^{\infty} ds\, \bar{L}\,(t,s) \tag{10}$$

The expression above (valid for a locally two-dimensional flow) has been derived for a blade of infinite length traveling rectilinearly. The three-dimensional aerodynamic and acoustic effects of blade rotation and finiteness of blade length are modeled as follows: the acoustic pressure p satisfies the three-dimensional stationary medium wave equation; the unsteady loads on the blade passing through the tower wake are taken to be equal to the two-dimensional sectional load given in (10) with the local blade velocity (and thus the magnitude of the loading) varying linearly from hub to tip. Given the assumption we have made here about the tower wake being the same for all points along the vertical (from blade tip to hub), such a model for the actual three-dimensional loading on a rotating blade, which sees a relative free stream linearly increasing in the tip direction, should be reasonably accurate except at a small region near the tip; here it overestimates the actual dipole strength since the latter must vanish as $\sqrt{R-r'}$. We solve the three-dimensional wave equation subject to the boundary condition

$$\Delta p(r',y) = \begin{cases} \frac{r'}{R}\, L(t)\,\delta\{\frac{c}{2}(y-t)\} & \text{for } 0 < r' \le R \\ 0 & \text{for } r' > R \end{cases} \tag{11}$$

where, as before, r' stands for the radial distance from the hub measured on the rotor plane. All spatial variables have been normalized by the blade semichord c/2, and time by $(c/2)/\Omega R$.

The solution of the above boundary value problem has the following form in the far field:

$$p(r,\tfrac{z}{r},\tfrac{y}{r},\tfrac{r'}{r};t) = \frac{iMR}{2\pi rc}\int_{-\infty}^{\infty} ds\; s\, L_o(s)\, D(s;\tfrac{z}{r},\tfrac{y}{r},\tfrac{r'}{r}) \cdot \exp\left[is(Mr-t)/(1-M\tfrac{y}{r})\right] \tag{12}$$

with

$$D(s;\tfrac{z}{r},\tfrac{y}{r},\tfrac{r'}{r}) = \frac{z}{r}\cdot\frac{1}{(1-M\frac{y}{r})^2}\cdot\frac{1}{R}\left\{\frac{\exp[-isRM(r'/r)/(1-M\frac{y}{r})]-1}{R\,[M(r'/r)s/(1-M\frac{y}{r})]^2} + \frac{i\exp[-isRM(r'/r)/(1-M\frac{y}{r})]}{s[M(r'/r)/(1-M\frac{y}{r})]}\right\} \tag{13}$$

Here, r is the distance between the observer in the far field and the turbine hub, and z is the projection of this distance on a plane normal to that of the rotor. M is $\Omega R/c_o$, the tip Mach number.

The directivity factor $D(s;z/r,y/r,r'/r)$ in (13) reaches a maximum in magnitude when $r'/r = 0$, that is, at points in the acoustic field which coincide with the rotor axis. Naturally, for a given r there are two such points -- one upstream of the turbine and one downstream. The fourier transform W(s), of the tower-wake upwash on the blade, was computed numerically with 2048 sample points using a Fast-Fourier Transform routine; so was the acoustic pulse in the far field as given by (12).

DISCUSSION OF RESULTS

A. Predictions of Gutin Noise

Figure 3 shows predicted directivity patterns at one kilometer from MOD-1 for the first three harmonics of the acoustic pressure for an operating condition of 35-RPM rotor speed and a 35-MPH free stream; the sound pressure level had a maximum value of 56 dB in the direction $\psi = 65°$. Figure 4 corresponds to the 35-MPH free stream, 23-RPM condition, for which the maximum level was 50 dB. A value of zero pitch at the blade tips was used in both sets of calculations.

For both uniform-flow operating conditions studied here we found that the predicted spectrum had the expected feature of containing only a few harmonics of significant level; therefore, the time signals (not shown here) were essentially pure sine waves at the blade passage frequency. Also as expected, the predicted Gutin directivity patterns indicated zero on-axis sound and a preference for radiation in the upstream direction of the turbine. Finally, we also confirmed that the case of lower rotational speed (23 RPM) radiates less overall Gutin noise than that of 35 RPM.

B. Predictions of Sound due to Ground Shear

Because the ground shear produces unsteady blade loads that vary with position around the rotor disk, the sound field is a function of both the angle ψ and angle in the rotor plane γ. Normally, for an observer on the ground far from the rotor, γ will be essentially 90°. However, if the observer is at a position in the field which is close to the rotor or much higher or lower than the horizontal plane of the turbine's base, acoustic predictions at other values of γ may be of interest. Our numerical results indicated however that the dependence on γ is very weak.

Figure 5 shows the predicted directivity pattern at one kilometer from MOD-1 for the first three harmonics of the acoustic pressure for $\gamma = 90°$; the maximum sound pressure level was found to be about 58 dB in the direction of $\psi = 65°$. The operating condition for the turbine was a 35-RPM rotor speed, zero blade tip pitch, and the previously described linear-shear free stream. Figure 6 shows similar predicted results for the operating condition of 23 RPM, zero blade tip pitch, and the same ground-shear profile. The maximum sound pressure level was found to be about 52 dB for this case.

In conclusion, in contrast to the acoustic directivity patterns for Gutin noise, those for ground shear indicated non-zero values of on-axis sound levels, due mostly to the higher harmonics. This relative growth of the higher part of the spectra is apparent also at the field points where the calculated sound pressure levels had maximum values in that the shapes of the acoustic signals there (not presented here) had slightly steeper slopes than those for Gutin noise. Accordingly, the maximum sound levels were higher than those obtained for uniform rotor inflow; the difference came from the added contribution to the sound field of the unsteadiness of blade forces, an acoustic source which of course is absent when the incident rotor inflow is uniform.

C. Predictions of Sound due to Tower-Wake/Blade Interaction

Figures 7a-c for 35 RPM show predicted acoustic signals at one kilometer from MOD-I for the wind-tower angles of 0°, 20°, and 45°, for which we obtained predicted sound levels of 85, 83, and 84 dB respectively, at the field point of maximum acoustic pressure (0° azimuth). These values are in good agreement with the amplitude of the measured signal shown in Fig. 8 (ref. 8). The signal in Fig. 8 was recorded approximately one kilometer from MOD-I and at a position in the field 24° in azimuth off the turbine's axis (see Fig. 10 below); by definition the direction of the wind corresponds to a 0° azimuth. The predicted time signals for the 23-RPM case were qualitatively similar to those shown here for 35 RPM but with the substantially lower values for maximum amplitude of 74, 72, and 73 dB for wind-tower angles 0°, 20°, and 45°, respectively. Figure 9 shows the predicted sets of spectra of these computed acoustic signals for the two cases of 35 and 23 RPM. Figure 10 shows the predicted simple acoustic dipole directivity pattern at one kilometer for the case of 35 RPM and wind-tower angle of 0°; the position in the field corresponding to that where the acoustic measurement in Fig. 1 was taken is indicated.

CONCLUSIONS

Based on the predictions of the models, we conclude that neither steady blade loads nor loads due to operation in ground shear contribute substantially to the acoustic signal from a wind turbine such as MOD-I. However, comparison of the theoretically predicted signal for noise from interaction with the mean wake (Fig. 7a) for a 35-RPM rotational speed, 35-MPH wind speed, 0° wind-tower angle, and the measured one shown in Fig. 8 indicates a close resemblance, both quantitatively and qualitatively. The conclusion to be drawn from this that high level impulsive sound could radiate from MOD-I due to the interaction of its blades and tower wake.

The results for the 23-RPM case suggest that a possible way to reduce a turbine's acoustic output is to operate at a lower rotor speed. Instead, dramatic noise reduction could be achieved without compromising performance by changing the structural configuration of towers to have smoother wakes. To accomplish this, the relationship of complicated tower geometries and their wakes will have to be investigated experimentally in follow-on studies. Earlier we had pointed out that cross flows into the rotor might have significant acoustic effects. Investigation of this possibility should also form part of future experimental and theoretical research.

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NOMENCLATURE

A_s	Fourier components of the flat-plate load shape functions, Eq. (1)
B	number of blades - two for MOD-I
$B_q^{I,T}$	Fourier coefficients of I, T, respectively, given in Eq. (5)
c	local blade chord
c_o	sound speed
D	directivity factor, Eq. (13)
I	magnitude of computed in-plane blade force
J_n	Bessel function of order n
$\bar{L}$	unsteady lift acting on a blade passing through a gust, Eq. (9)

L_o magnitude of unsteady lift due to blade/gust interaction given by Filotas' theory, term in brackets in Eq. (9)

M blade tip Mach number

p acoustic pressure

P_s harmonics of the acoustic pressure signal p

r distance of observer in the far field from turbine hub

r' radial distance measured on the plane of the rotor disk

R rotor radius

s harmonic counter

T magnitude of computed thrust blade force

t time

W Fourier transform of w

w downwash felt by the blades as they cross the tower wake

y distance measured across the tower wake normal to the free stream direction and tower center-line

z distance normal to rotor disk

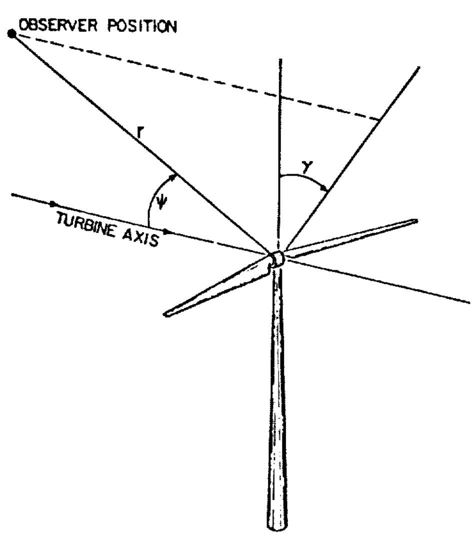

Figure 1: Coordinate system used in the Gutin and ground-shear models.

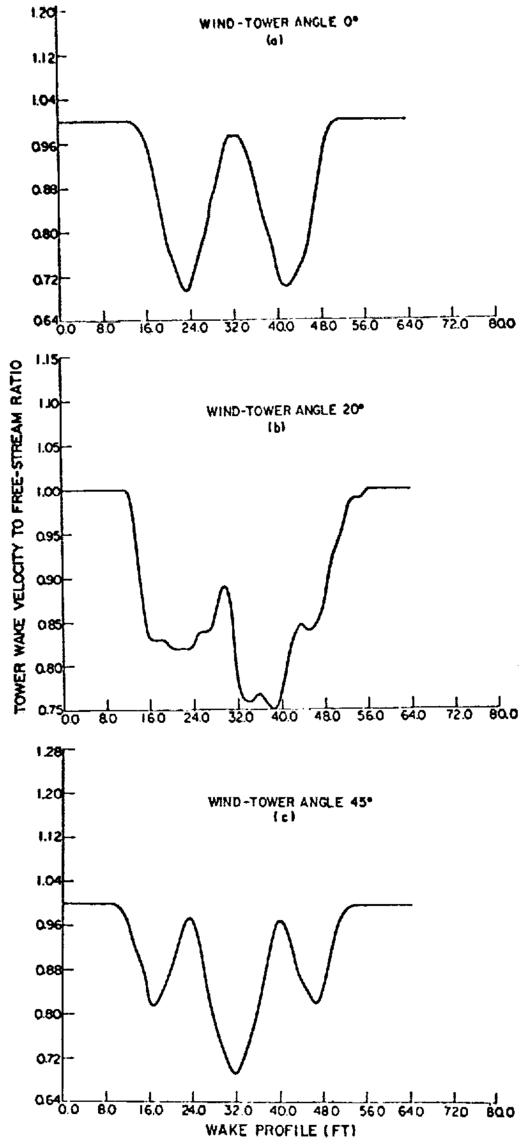

Figure 2a-c: Tower-wake velocity profiles from ref. 7. Abscissa has been scaled to actual MOD-I dimension.

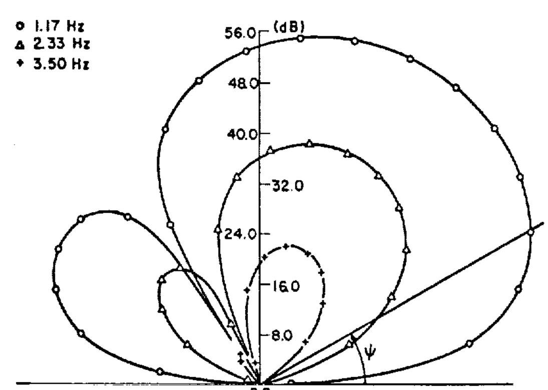

Figure 3: Directivity pattern at 1 Km of first three harmonics of Gutin noise for free stream of 35 MPH, $\Omega = 35$ RPM.

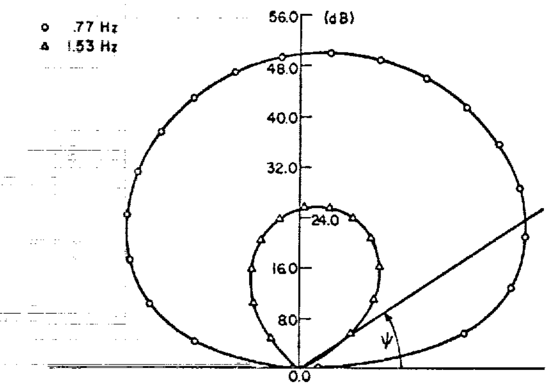

Figure 4: Directivity pattern at 1 Km of first three harmonics of Gutin noise for free stream of 35 MPH, $\Omega = 23$ RPM.

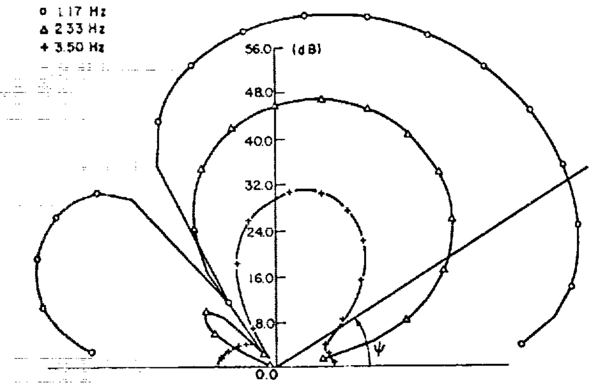

Figure 5: Directivity pattern for $\gamma = 90°$ at 1 Km of first three harmonics of acoustic signal due to operation in a linear Ground Shear of 8 MPH for free stream of 35 MPH, $\Omega = 35$ RPM.

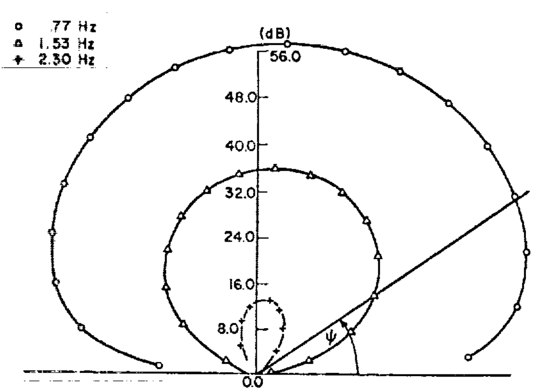

Figure 6: Directivity pattern for $\gamma = 90°$ at 1 Km of first three harmonics of acoustic signal due to operation in a linear Ground Shear of 8 MPH for free stream of 35 MPH, $\Omega = 23$ RPM.

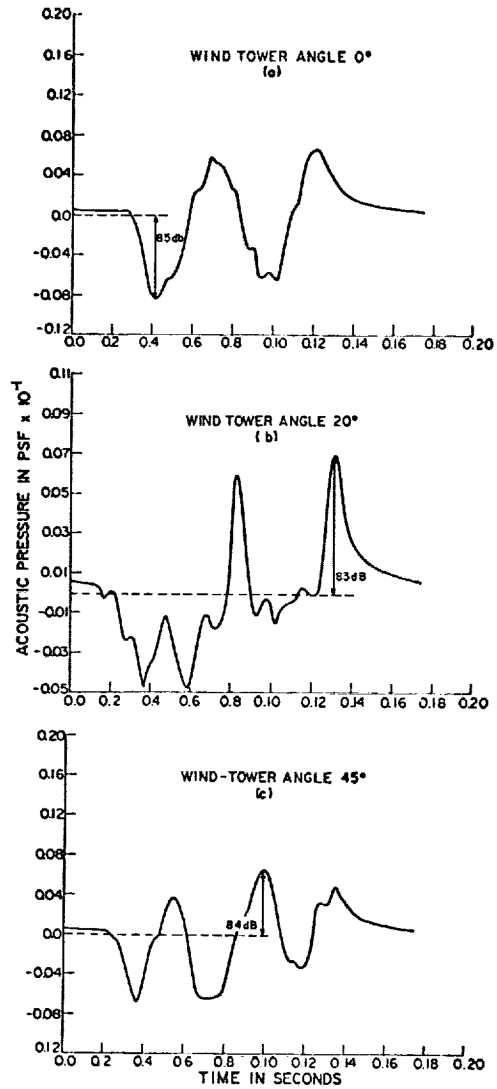

Figure 7a-c: Predicted acoustic signals at 1 Km at field point where sound pressure level was maximum for free stream of 35 MPH, $\Omega = 35$ RPM.

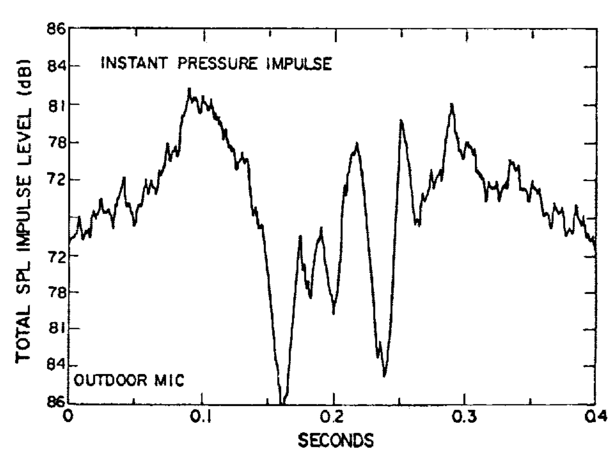

Figure 8: Measured acoustic signal at 1 Km, 24° off turbine axis for $\Omega = 35$ RPM (from ref. 8).

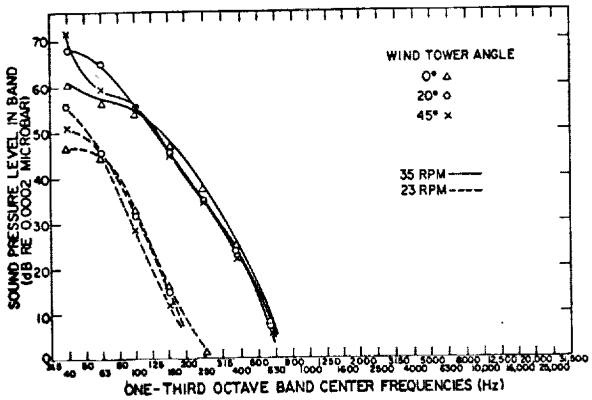

Figure 9: Spectra of predicted acoustic signals at 1 Km for $\Omega = 23, 35$ RPM; wind-tower angles 0°, 20°, 45°.

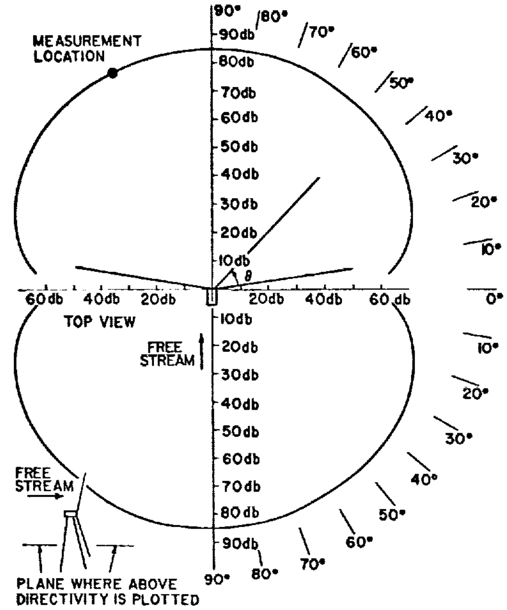

Figure 10: Predicted acoustic directivity pattern for tower-wake model for wind-tower angle of 0°. Location of measurement is indicated in the acoustic field.

QUESTIONS AND ANSWERS

W.L. Harris

From: F.W. Perkins

Q: Will any internal structural changes to the blades reduce impulsive noise significantly?

A: *No. Structural changes in the blades, within limitations of maintaining reliable blades, will not influence the tower wake. A small reduction in the amplitude of impulsive noise may be observed if a "softer" blade is used.*