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STATUS REPORT

ON

DOWNWIND ROTOR HORIZONTAL AXIS WIND TURBINE NOISE PREDICTION

BY

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ABSTRACT

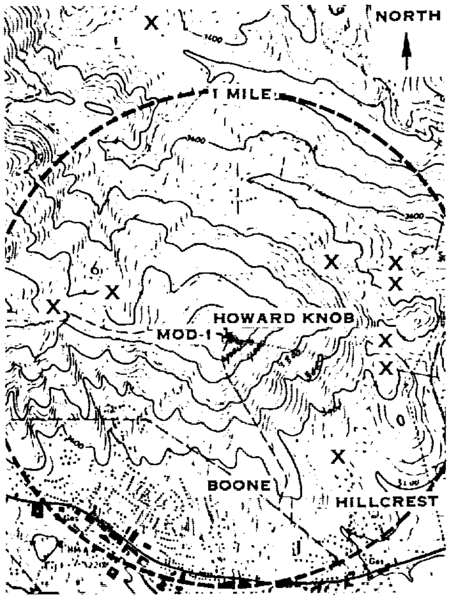
NASA and industry are currently cooperating in the conduct of extensive experimental and analytical studies to understand and predict the noise of large, horizontal-axis wind turbines. This effort consists of (1) obtaining high quality noise data under well-controlled and documented test conditions, (2) establishing the annoyance criteria for impulse noise of the type generated by horizontal-axis wind turbines with rotors downwind of the support tower, (3) defining the wake characteristics downwind at the axial location of the plane of rotation, (4) comparing predictions with measurements made by use of wake data, and (5) comparing predictions with annoyance criteria. This report briefly summarizes the status of work by Hamilton Standard in the above areas which was done in support of the cooperative NASA and industry studies.

INTRODUCTION

Work is now under way at NASA and in industry to understand wind turbine noise generation mechanisms. All aspects of this problem are complex, so the progress has been limited. The information in this report describes the work done at Hamilton Standard with the assistance of NASA and other investigators in industry. It is emphasized that the statements made in this report are in many cases tentative and subject to change as more information becomes available.

Annoyance Problem

In the past, many wind turbines have been built and operated with no indication of a noise problem significant enough to prompt an investigation or apply any noise control measures. This is also true of all currently operating wind turbines except for the MOD-1 at Boone, North Carolina. The noise heard at the Boone site has been described as a thumping noise which is annoying, mainly when heard indoors. As shown in Figure 1, the complaints have been received from residents within 1 1/4 miles of the MOD-1 site. Also, it is of interest to note that the complaints are received from residents outside the towns in the area. This indicates that the very quiet background noise at less populated locations may allow even low levels of wind turbine noise to be heard. It can also be seen from the topographic information in Figure 1 that many of the compliants are received from sites 1000 ft. below the height of the MOD-1. Thus it is possible that high wind velocities could exist at the MOD-1 location, but the wind velocity at the complaint site might be negligible. This would also lead to a very quiet ambient background noise in which even faint sounds from a wind turbine might be heard. In a fairly level site the high winds that drive a wind turbine would also raise the background noise at a residence, so the wind turbine noise would tend to be inaudible.



X INDICATES COMPLAINT LOCATION

Figure 1 - Complaint locations at MOD-1 site

The characterization of the annoying noise as a "thump" rather than a "swish" indicates that it is impulsive in nature and due to interaction of the wakes from the tower legs with the rotor, i.e., the wake velocity deficit downwind of a tower leg causes a sharply flutuating lift on the rotor which is radiated as impulse noise. A sample of these impulses is shown in Figure 2. Here the sound pressure level as a function of time is plotted at a location outside a house at Boone where complaints were generated. Each of the sharp pulses of Figure 2 are caused by the passage of a rotor blade through the tower wake. Spectrum analysis of characteristics of the noise in the near field, 205 ft. from the MOD-1, outdoors at a complaint location 3000 ft. from the MOD-1, and inside a complainant's house are shown in Figure 3. Figure 3 shows that the impulse character of the noise is found only below 31 Hertz as evidenced by the multiple humped envelope of the spectrum shape seen at the upper left. Above 31 Hertz it is not possible to identify the character of the sound and it is conjectured that the impulse character of the noise is confined to frequencies below 31 Hertz. In fact, it is even more difficult to identify impulse character in the far field outside or inside a complainant's house. It should also be noted that Figure 3 is typical of the data from MOD-1 which has been analyzed.

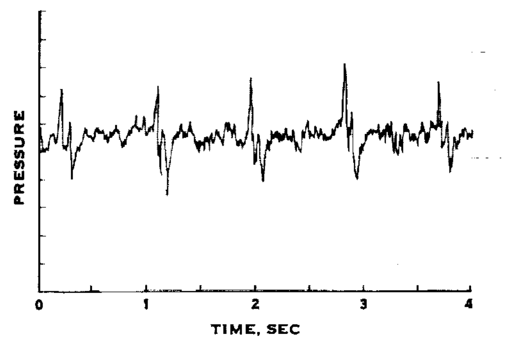


Figure 2 - Pressure impulse sequence recorded outside of complainant's home (data from unpublished NASA Langley Report Jan 26, 1980)

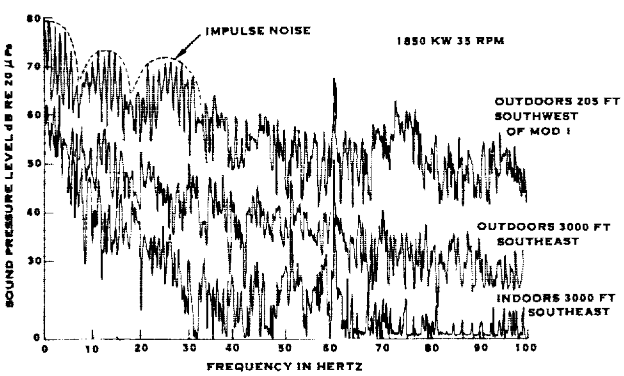


Figure 3 - MOD 1 noise spectra

Prediction Method

In order to predict the noise of a wind turbine Hamilton Standard has adapted the theoretically-based methodology used for predicting propeller noise. This method uses an extension of the theory contained in (ref. 1). A block diagram for this methodology is shown in Figure 4. This methodology calculates tone noise due to steady loading associated with the volume of the blade, and unsteady loading caused by the wind shear and tower wake defect. Broadband noise due to turbulence at the trailing edge of the blade or due to interaction of the blade with inflow turbulence is also calculated. The method is capable of evaluating the influence of ground reflection on measured noise, but this feature has not yet been considered necessary for wind turbine predictions.

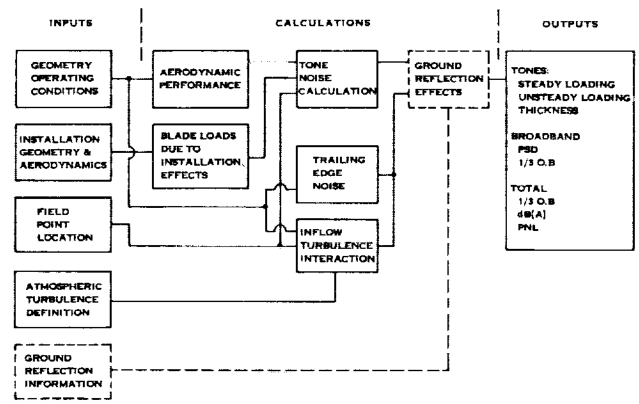


Figure 4 - Far-field rotor noise calculation procedure

The method is computerized and is a far-field time domain method, i.e., it will calculate noise only at locations a minimum of several rotor diameters from the wind turbine, and the output of the calculation is a frequency spectrum. In order to run cases, the performance of the rotor is calculated, and the characteristics of wake velocity defect and wind shear are used to calculate unsteady blade loads. These two sets of input information are used to calculate the tone noise components of the noise spectrum. The impulse character of the noise due to the wake defect is calculated by the tone noise program. For the present annoyance studies, broadband noise due to trailing edge or inflow turbulence has not been considered.

Correlation of Measurement and Prediction

An indication of the accuracy of the method can be seen in Figure 5 where the outdoor far-field spectrum of Figure 3 is compared with an envelope of harmonics predicted by the method of Figure 4. As input, this calculation used wake definition derived from the model tests of (ref. 2). It can be seen that the impulse character of the spectrum up to about 30 Hertz is fairly well predicted. However, above this frequency the prediction falls below the measurement and it is not possible to identify the character of the measured spectrum.

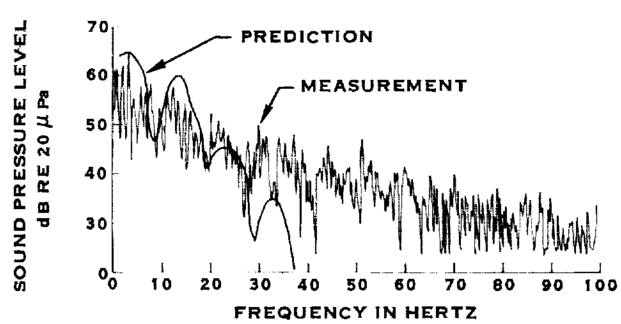


Figure 5 - Comparison of prediction measurement for MOD-1

The lack of agreement between prediction and measurement is believed due primarily to the specification of the tower wake which causes the fluctuating lift on the rotor. As indicated above, the wakes used for the predictions of Figure 5 were derived from wind tunnel model tests of a MOD-1 tower. To use this data the wake characteristics of the full-scale tower had to be inferred from measured wakes in model scale obtained at a distance downwind of the tower which differed from the full-scale, tower-to-rotor spacing. Also, it was assumed that the Reynold's number of the flow in model and full-scale were similar. Therefore, it can be seen that the disagreement between predictions and measurements might be considerably improved if full-scale wake data were available for noise calculations.

The lack of wake data in the literature obtained at distances downstream of the tower at rotor-to-tower clearances being used in wind turbine design has prompted NASA to sponsor model wind tunnel tests at Wichita State University. Wake definition as a function of Reynold's number at several downwind distances close to the tower will be established for smooth cylinders having various radii on the corners. This data will be particularly valuable for noise predictions of wind turbines with single-shaft towers. Analysis of this data is not yet complete but early results indicate that the published wakes (ref. 3) for cylinders may not be reliable as the basis of wake definition for noise calculations. The deficiency in the published wake data appears to be due to the use of measurements obtained in the far wake, 10 or more diameters downstream of a cylinder. When this data is extrapolated to locations closer to the tower, wake width and wake velocity deficit do not appear to agree with Wichita State data.

Noise Annoyance Criteria

Annoyance caused by noise from any source is a problem which has been addressed by municipal and federal governments with increasing emphasis in recent years. Noise control ordinances have been written in many communities to insure that the noise of mechanical equipment used in everyday life does not compromise the character of the living environment. There are many methods for evaluating the annoyance potential of a sound. However, these methods have primarily addressed sounds with a broadband character or ones with pure-tone components. Impulse noise is addressed, but impulse noise corrections may not be applicable to the impulse characteristics of wind turbine noise.

Therefore, NASA-Langley has conducted limited psychoacoustic tests in an attempt to identify annoyance criteria for wind turbines. The following discussion makes use of the NASA-Langley results plus other available information in order to establish some tentative noise annoyance criteria for wind turbine noise. It is recognized that NASA-Langley is continuing psychoacoustic research and that there is a limited understanding of the character of wind turbine noise spectra. Therefore, the criteria below should be considered tentative and the starting point for further development.

NASA-Langley, in unpublished reports, has taken the position that wind turbine impulse noise will probably be unacceptable if it can be heard. This is a very stringent criteria and one which has not been accepted in establishing the annoyance of other noise sources. In general, the rating systems such as ISO R 1996 (ref. 4) allow some exceedance of the criteria before sporadic complaints are expected. However, it is certainly true that wind turbine noise that is inaudible will be completely acceptable. Therefore, the NASA-Langley work will be used as a starting point for development of the tentative criteria discussed below.

Figure 6 shows the basis for the proposed tentative criteria. The curve labelled 'Impulse Noise Criteria' was obtained by drawing a line through the spectrum of a wind turbine impulse noise where the spectrum shape was adjusted such that it could just barely be heard in a quiet background noise in an anechoic test chamber. Since listeners in real life environments do not listen to wind turbine noise in completely quiet background noise, the two curves of Figure 6 for wind noise at 20-30 mph and 0-10 mph as heard indoors were developed by applying the assumed noise attenuation at the bottom of Figure 6 to measured outdoor wind noise spectra. Also, it has been stated earlier that the character of wind turbine noise above 31 Hertz cannot be clearly identified as impulse in nature, so another line for minimum audible field for tones or broadband noise is required. For this, the minimum audible field lines in Figure 6 were plotted. The upper curve is one contained in an unpublished NASA-Langley report of June 26, 1980 and the lower curve is one contained in ISO R 226 (ref. 5). The higher of these two curves will be used as the basis for further discussion in this paper. However, it is certainly subject to change as the character of wind turbine noise becomes better understood and additional psychoacoustic tests are conducted.

Based on the above discussion, several criteria are suggested in Figure 6:

1. If the noise is impulsive in nature it must exceed the line marked 'Impulsive Noise Criteria' at some point in the 1/3 octave band spectrum. However, if the impulse noise is heard in a background noise caused by wind at 20-30 mph, the impulse noise must also exceed the line marked 'Indoor Wind Noise Estimate 20-30 mph'. If the background noise is due to wind at 0-10 mph, then the impulse noise would be audible if at some point it exceeded the curve marked indoor wind noise estimate 0-10 mph.

2. If the wind turbine spectrum is not impulse in nature, then noise levels that do not exceed the curve marked minimum audible field (whole body) are considered acceptable.

From the above discussion it is clear that the nature of the various portions of the wind turbine noise spectrum must be understood to apply the criteria. This will require further work.

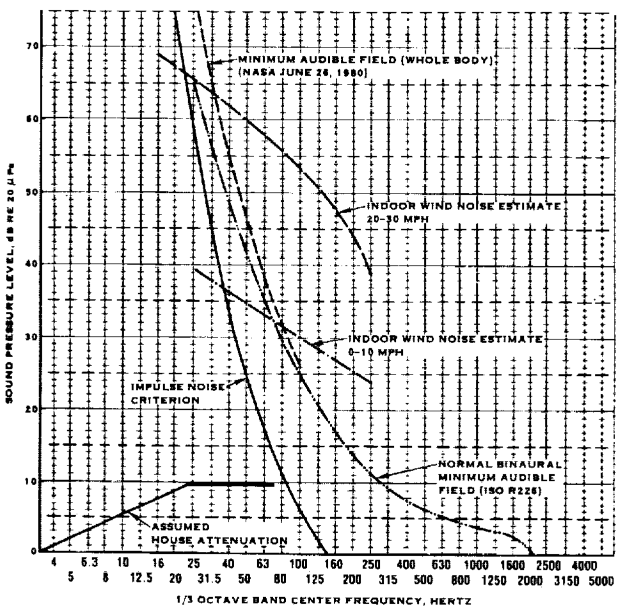


Figure 6 - Basis/or tentative annoyance criteria

Application of Tentative Noise Criteria

Figure 7 demonstrates the application of the tentative noise criteria. Here a 1/3 octave band spectrum at an operating condition of 1850 kW and 35 RPM, measured in a complainant's home, is plotted. This is a 1/3 octave band version of the narrowband spectrum plotted in Figure 3. Since the complainant's home was in the valley below the MOD-1 site, it will be assumed that the 0-10 mph wind criterion applies. Also, as indicated earlier in the discussion of Figure 3, the noise at frequencies greater than 31 Hertz is not believed to be impulsive. Figure 7 shows that the measured spectrum exceeds the impulse criteria and the 0-10 mph wind criteria only by a small amount of 40 Hertz. Also, the prediction of Figure 5 has been converted to 1/3 octave bands, the house attenuation of Figure 6 applied, and the result plotted in Figure 7. Relatively good agreement with measurements is shown at frequencies below 31.5 Hertz. From Figure 7 it is tentatively concluded that annoyance at the complainant's house, due to MOD-1 operation, should be negligible. If, on the other hand, the annoyance at the complainant's house is indeed considered significant, then the tentative criteria discussed in this report must be revised.

Noise Reduction Concepts

Figures 6 and 7 indicated that annoyance can be eliminated by minimizing the high-frequency components of wind turbine noise. Also, if the measurements and predictions of Figure 7 are typical of the wind turbine noise problem, then only a small change in configuration may be required to eliminate the problem.

One possibility for reducing noise at higher frequencies is to reduce rotor design RPM. For the MOD-1, the design speed was originally 35 RPM. A reduction in design speed to 23 RPM is expected to reduce noise by about 10 dB, particularly at higher frequencies. On the basis of the measurements in Figure 7, such a reduction should eliminate the annoyance problem on MOD-1. There is, however, some energy capture penalty for such a modification.

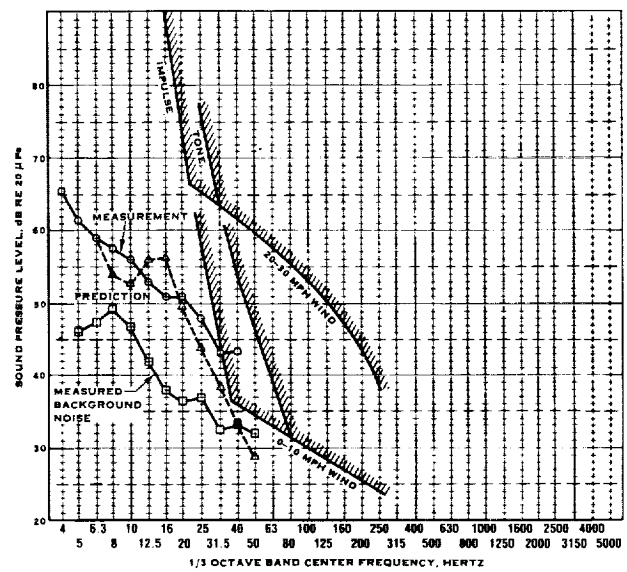


Figure 7 - Evaluation of predictions and measurements relative to tentative annoyance criteria

Other alternatives which may have no energy capture penalty are modifications to the tower. Guidance for beneficial changes to wind turbine support towers is contained in Figures 8 and 9. These figures are based on a simplified analytical study of wind turbines with downwind rotors and cylindrical towers. In Figure 8 it can be seen that a narrow wake with a large wake defect is the worst case for producing high-frequency noise. If the velocity defect is minimized, then the noise at all frequencies is reduced. If, in addition, the width of the wake is increased, then the high-frequency noise is suppressed.

Figure 9 indicates the best shape for a wake defect from a noise reduction standpoint. The shape derived by Schlicting from test data on smooth cylinders (ref. 3) is seen to cause the highest level of high-frequency noise. A wake with cosine-squared shape produces less noise and, surprisingly, a Gaussian wake produces no high-frequency noise. The message from Figure 9 is that high-frequency noise might be eliminated if the tower could in some way be modified to produce a Gaussian wake. Also, very small differences in the wake shape assumed for a noise calculation can have a large effect on the high-frequency components of noise predicted. The implied sensitivity of the calculation procedure to small changes in wake definition indicates the need for additional work to correctly model full-scale tower wakes.

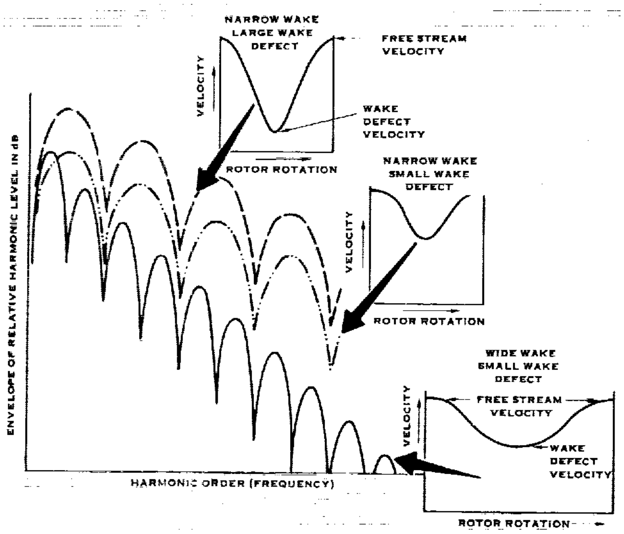


Figure 8 - Effect of wake defect amplitude and width on noise spectrum shape

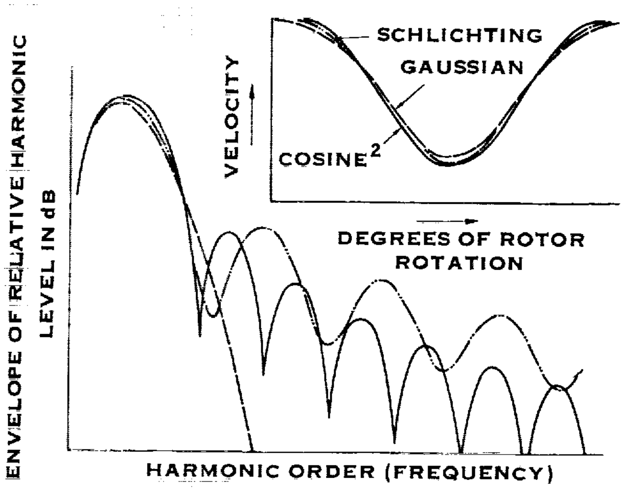


Figure 9 - Effect of wake velocity defect shape on noise spectrum shape

CONCLUDING REMARKS

At present there is a limited understanding of the annoyance problem at the MOD-1 site. This problem appears to be unique as there have never been any annoyance problems due to operation of other wind turbines. However, in order to prevent such problems at future turbine sites it is important that the MOD-1 noise is completely understood. Evaluation and control of noise of future wind turbines requires further work in three areas: (1) noise annoyance criteria which correctly reflect the actual annoyance response of residents living around existing wind turbines, (2) accurate noise prediction procedures for use in predicting noise of new wind turbine designs and for conducting analytical noise control studies, and (3) definitive noise measurements of sample wind turbines for use in testing prediction methods and annoyance criteria.

At the present time there are deficiencies in all three areas. Noise annoyance criteria for impulsive noise must be developed and their accuracy must be established. Noise prediction procedures such as that described in this paper appear capable of accurate predictions, but substantial work is needed to define the wakes as input to the calculation procedure. Finally, additional reference wind turbine noise measurements are needed which have been obtained under carefully controlled conditions in the far acoustic field at test sites with terrain and vegetation that does not cause unpredictable changes in the data.

Acknowledgement

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QUESTIONS AND ANSWERS

F.B. Metzger

From: F.W. Perkins

Q: Would a swept tip on the blade effectively broaden the wake, and reduce impulsive noise?

A: *Yes. However, it is not clear how much sweep is required and how much of the blade must be swept to cause a significant reduction.*

From: P. Abbot

Q: Do you believe that the wake deficit is the sole problem of the low frequency noise and if so, why don't we see this occurring (always) from the data? What is your feeling about the turbulence on the wake?

A: *Yes. There are nonrepetitive characteristics of the wake and atmospheric variations which may prevent noise generation from being consistent. Turbulence in the wake would lead to less annoying random or broadband noise generation.*