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Appropriate resolution models for MINI wind turbine noise

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Abstract

In the early stages of design, there may be few input data available which can be used to predict noise from a wind turbine. This makes consideration of noise difficult until the blade specification is practically finished. In recent work, (MINI Wind Turbine of 13m rotor diameter, power output 7-10kW, produced by Tozzi Nord), we have used very simple line source models to estimate noise from wind turbines, based on the data from initial aerodynamic designs. We present a comparison of results from these very crude models with data from more sophisticated techniques which can be used in the later part of a design, and also measured data. We find that even simple models give results which, if interpreted with care, can allow rational decisions on noise output to be made, to engineering accuracy, even when data on broadband sources on the blade are not known. This finding allows simple models to be implemented in the very early stages of design to allow alternative geometries to be ranked with respect to their noise output, with some reasonable confidence.

Introduction

One of the major factors affecting acceptance of wind turbines as a power source, is the noise which they generate, or are perceived to generate. For this reason, it is desirable to include an assessment of noise early in the design process, allowing the possibility of optimizing a design to reduce noise to an acceptable level, possibly with some reduction in efficiency, but allowing a new design to be sited where it might be useful. This is especially important for small turbines which are designed to be sited near homes and other buildings, for example in supplying power to schools and similar establishments. In this case, acceptance by the user group is essential both for immediate implementation of the power plant and for the possible development of wind energy solutions in the future. If a small, local plant is judged too noisy, there will be greater community opposition to future larger systems.

There are a number of different methods available for prediction of noise from wind turbines, which to a greater or lesser degree implement physics-based models for

the known source mechanisms. The aim of this paper is to compare two such models, one very simple approach, based on the loading distribution on the blades, and one sophisticated, industry-standard method, which computes aerodynamics and noise including the various turbulent source mechanisms which are known to be important in the audible range. Our aim is to assess the noise predictions made by the simpler model, which can be used when only limited data are available, such as in the early stages of design, by comparison with the results from the more complex model which uses all of the detail available. As a case study, we consider the design of a recently developed mini turbine to be produced by Tozzi Nord. The fundamental question to be answered is:`at the earliest stage of design, how well can we assess the noise produced by a turbine?'

Noise models

The two models which are used in performing calculations are a simple `line source' model for tonal noise and the FAST model, developed by the US National Renewable Energy Laboratory (NREL).

The first, simple, model is based on the representation of the turbine rotor by a line distribution of forces, given by the axial and azimuthal loads on the blades. This is a model which can be implemented using the most basic data available for a rotor, the loading distribution, with the consequent disadvantage that it can only predict tonal noise. In effect, in using this model, we make the tacit assumption that the noise levels predicted for the (low frequency) tonal components will scale in the same manner as the (higher frequency) turbulent and trailing edge noise terms, so that the tonal noise can be used as a proxy to indicate the relative noise levels of different design iterations.

The noise radiated from a point force f is given by the standard expression:

$$p(\mathbf{x},t) = -\nabla.\frac{\mathbf{f}(\mathbf{y},t-\frac{R}{c})}{4\pi R}$$

where x and y are the observer and source points respectively, R is the source-observer distance and *c* is the speed of sound. Upon integration over the rotor disk, this gives:

$$p(x,t) = -\nabla.\int_0^a\int_0^{2\pi}\frac{f(y,t-\frac{R}{c})}{4\pi R}r_1 dr_1 d\theta_1$$

where the source is written using cylindrical coordinates (r_1,θ_1). In a cylindrical system of coordinates, the force distribution can be written as a Fourier series:

$$f(r_1,\theta_1)=\sum F_n e^{jn(\theta_1-\omega t)}$$

where ω is the turbine rotation speed, and inserted into the radiation integral to give the noise radiated at each multiple of the blade passage frequency (Wright 1969; Gutin 1948):

$$P_n=\frac{jn}{r}\iint\frac{e^{j(kR+n\theta_1)}}{4\pi R}F_\theta(r_1)r_1 dr_1 d\theta_1+z\iint\frac{e^{j(kR+n\theta_1)}}{4\pi R}(jkR-1)F_z(r_1)r_1 dr_1 d\theta_1$$

where F_z is the axial component of force on the blade at radius r_1 and F_θ is the azimuthal (torque) component. The wavenumber $k=n\omega/c$

This is the simplest model which can make reasonable predictions of the noise radiated by a rotor and is readily implemented using a simple computer code which reads the output of a `lifting line' type calculation. The Sound Pressure Level (SPL) is computed by summing the contribution from each tone, with no adjustment such as A-weighting. It has also been assumed that at the low Mach numbers typical of realistic wind profiles, the effect of the mean flow on noise propagation can be neglected. This would not be a good assumption for large systems whose noise propagates over large distances through strongly varying atmospheric conditions, but is reasonable for small turbines whose noise levels will be perceived quite close by.

The second model which we have used is the NREL FAST code (Jonkman & Buhl 2005) with the addition of a semi-empirical noise prediction scheme (Moriarty & Migliore 2003). This is a very sophisticated model for the aerodynamics, dynamics and performance of wind turbines. With the addition of the noise prediction scheme, based primarily on the prediction scheme of Brooks, Pope & Marcolini (1989), it uses a database of geometrical and aerodynamical information for the blade aerofoils estimate the noise generated by the main noise sources. These sources are the turbulent boundary layer trailing edge interaction, flow separation, laminar boundary layer vortex shedding, trailing edge bluntness and tip vortex formation. These sources are modelled using wind-tunnel measurements taken on two-dimensional aerofoils which have been processed to give empirical noise correlations based on Reynolds number, section Mach number, boundary layer displacement thickness and directivity functions. In the calculations for this paper, we have included all of these mechanisms and the effect of inflow turbulence. Sound Pressure Levels are presented as A-weighted sums of the third-octave band SPLs.

Turbine model

The turbine considered in this paper is TN535, Figure 1, an upwind MINI Horizontal Axis Wind Turbine, designed and produced by Tozzi Nord srl (Trento, Italy), specifically for low wind speed sites (class IV, according to IEC 61400-2). The turbine is rated 10 kW power and its rated wind speed is approximately 6.5 m/s. The rotor diameter is 13 m. Hub altitude is 18 m.The generator is synchronous with permanent magnets, gearless but with belt for the transmission. The turbine is pitch-controlled and has an active yaw system. Rotor speed is variable, ranging from approximately 20 to 66 rpm. At 66 rpm, rated power is reached. Cut-in and cut-out wind speed are respectively 2m/s and 16 m/s. Blade profiles are suited to low Reynolds numbers and the blade geometry is optimized to improve both the power performance and structural strength.

During the preliminary phase of the project we tried to make a choice of those design parameters that most influence the aeroacoustic emissions without compromising other performance of the turbine. One of the main parameters that influences the noise emission is the rpm, and TN535 remains low speed throughout its operation, being designed for sites with low wind speeds. Besides that, with regard to the geometry of the blades, a thin trailing edge was imposed. The shape of the blade tip

was investigated in the literature to reduce tip vortices (Wagner, 1996). From the available blade profiles with appropriate performance and operating speed were chosen those with good noise characteristics, on the basis of published data for other MINI wind turbines (Migliore et al, 2003) and several case studies reported in the literature .

Figure 1: The TN535 turbine

Noise predictions

The first set of predictions shown, Figure 2, show the variation of predicted noise level on the ground, over a range of axial displacements 50 metres upstream and downstream of the turbine rotor at a nominal wind speed of 7m/s. It is clear from the data presented that the noise predictions of the two models are very different in character. The broadband results from the FAST model have a lower maximum Sound Pressure Level but at large distances from the rotor the noise level is much higher than that predicted by the tonal model. This result is not unexpected: the broadband noise mechanisms generate sound at higher frequency than the tonal model and have a rather different directivity. Likewise, the tonal model generates higher maximum noise levels, but in a region just upstream and downstream of the rotor plane.

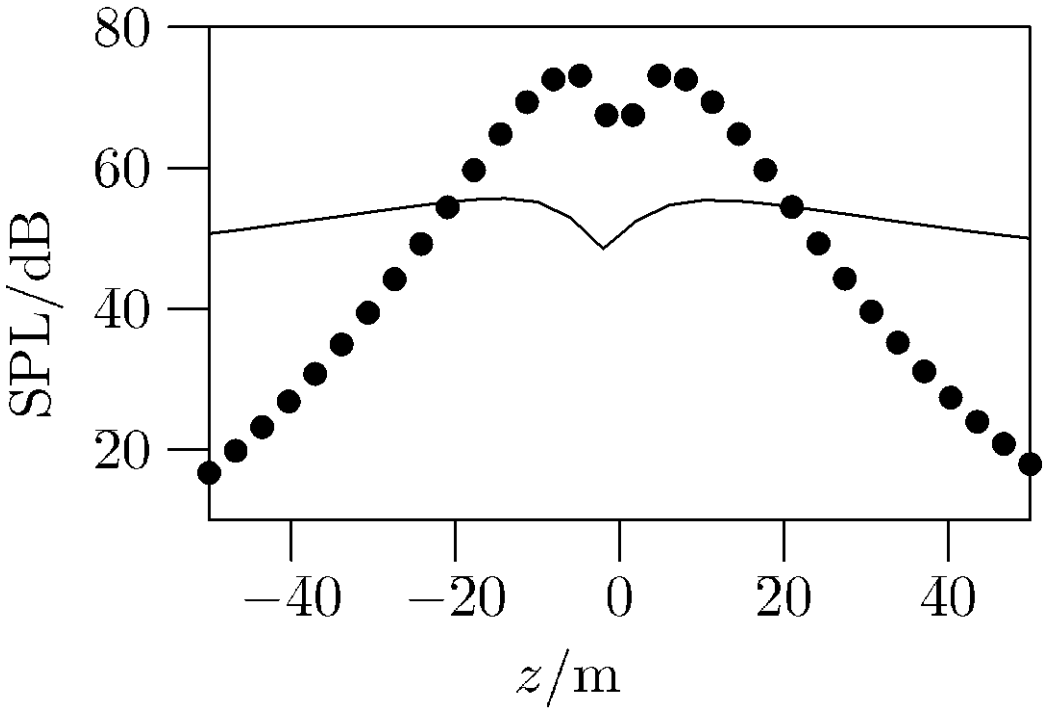

Figure 2: Predicted overall SPL for nominal wind speed 7m/s. FAST predictions shown as solid line, tonal model data shown as circles.

Obviously, the two models do not give the same results and the simple tonal model cannot be used to make predictions of absolute levels for use in deciding where to site a turbine. This is not our purpose in applying the technique, however. The aim is to implement a model which uses minimal data to correctly predict the trend of noise level as design parameters are varied. At the early stages of a design, the aerodynamic calculations are based on simple `lifting line' type models assuming a uniform inflow. Given this level of detail, the question is: `can we correctly predict how the noise level changes as the operating environment changes?'

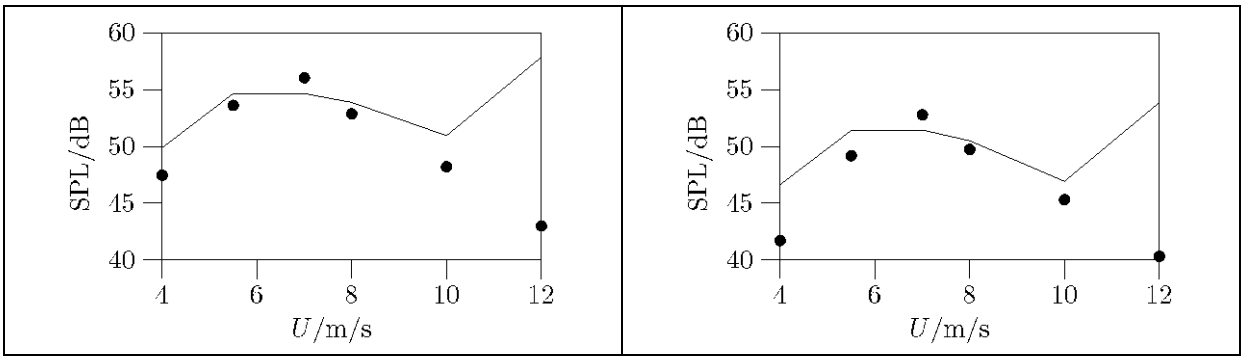

Figure 3: Variation of noise level with wind speed. Plot a: 20m downstream of rotor; plot b: 40m downstream of rotor. FAST predictions are shown as a solid curve, tonal model data are shown as circles. The tonal model predictions at 40m have been shifted up by 25dB (see main text for details).

Figure 3 shows the variation in overall SPL as a function of nominal wind speed, downstream of the rotor (results upstream of the rotor show similar trends). The measurement points chosen are on the ground, 20 and 40 meters downstream of the rotor centre. The match between the two prediction methods is very good at 20m, except for the different trend predicted as the wind speed increases over 10m/s. Otherwise, the tonal model follows the FAST data quite well over the range 4m/s to 10m/s. At 40m downstream of the rotor, it is clear from Figure 2 that there is a large difference between the two prediction methods. For this reason, to make the trends clearer, the tonal model predictions have been shifted up by 25dB in the second plot of Figure 3. With this shift, the trend in noise is again predicted quite well, over the range 4m/s to 10m/s, but fails to predict the increase in noise which FAST yields at 12m/s. The relevant point is that using the simple disk model would have correctly predicted the variation in noise level over the primary range of wind speeds.

The results for this test case show that it is possible to use a simple model to make decisions about the gross design of a rotor, using the basic aerodynamic data which are available. It is worth noting that running the simple tonal model takes very much less time than running FAST (which also performs a full aerodynamic and structural calculation) so it can be used in optimization of a design at an early stage. The point which must now be addressed is why this simple model works, given that it must obviously be interpreted with some care.

Model comparison

We have found that, for the test case considered, a simple tonal model and a sophisticated analysis tool predict the same trends in aerodynamic noise over the range of velocities relevant to a small turbine. If the simple model is to be used, it is important to understand why and how it gives good results for the trend, so that its predictions can be used properly in making decisions about new designs.

The correlations which the FAST code uses for noise prediction are described by Moriarty and Migliore (2003). For most of the mechanisms the SPL is given by an equation of the form:

$$SPL = 10 \log_{10} \frac{\delta^2 M^5 L D}{R^2} + K$$

where δ is the boundary layer displacement thickness, L is the blade section span, D is an empirical directivity function and *M* is the section Mach number based on the local velocity. The term K is composed of a number of terms which depend on the noise mechanism being considered. For a given blade geometry, the prediction equation can be summarized as composed of a part which scales with Mach number and boundary layer thickness and a Reynolds number dependent part which is measured empirically. The directivity is taken from measured data. Clearly, the directivity function is quite different from that computed for the tonal model, as is evident from Figure 2, but the scaling with blade section velocity will be similar in both cases. It is known (Parry & Crighton, 1989) that the noise from subsonic rotors is exponentially dominated by the source at the blade tip so the scaling with local Mach number can be expected to be the dominant cause of variation in the radiated noise. This scaling will be similar for the tonal and broadband models, though with a different amplitude. Furthermore, the steady blade loading should vary with the same parameters (Reynolds number, for example) as the terms which control the radiated broadband noise. In effect, the blade loading acts as a proxy for the broadband noise terms and yields a prediction for noise which varies with velocity in the same way as the detailed semi-empirical model, within the uncertainty of the data at the first stage of design. We conclude that, if proper precautions are taken, a simple tonal model can be used to assess the variation of noise with operating parameters of small scale turbines.

Conclusions

A simple model has been applied to the prediction of noise from a mini wind turbine. Comparison with the results from a sophisticated model which incorporates the full range of mechanisms responsible for noise from turbines has shown that while the low frequency, tonal model does not give predictions comparable to the noise from the full set of mechanisms, it does give results which scale in a similar manner. We conclude that a simple tonal model can be used with limited aerodynamic data to make rational choices about blade design in the early stages of a new project when simple, engineering methods are appropriate.

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