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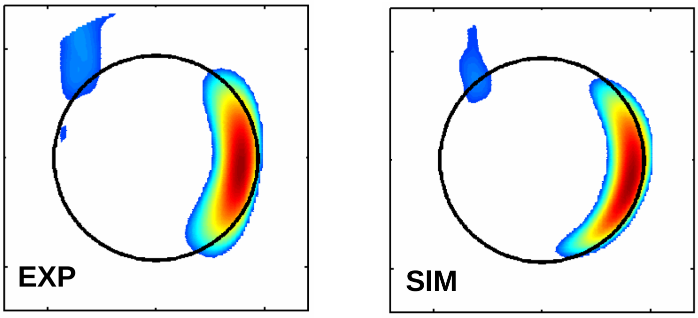
Executive summary

Prediction of wind turbine noise and comparison with experiment



Problem area

The availability of fast and accurate wind turbine noise prediction methods is important for the design of quiet wind turbines and for the planning of wind farms.

Description of work

This paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The prediction code only needs the blade geometry and the turbine operating conditions as input. The availability of detailed acoustic array measurements on the same turbines enabled a thorough validation of the simulations.

Results and conclusions

Generally a very good agreement was observed between experimental and simulated results, not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position. The deviation between predicted and measured overall sound levels (as a function of rotor power) was less than 1-2 dB for both turbines, which is smaller than the scatter in the experimental data.

Applicability

All in all, the present study provides a firm validation of the prediction method, which therefore is a valuable tool for the design of quiet wind turbines and for the planning of wind farms.

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Contents

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PREDICTION OF WIND TURBINE NOISE AND COMPARISON WITH EXPERIMENT

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Abstract

This paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The prediction code only needs the blade geometry and the turbine operating conditions as input. The availability of detailed acoustic array measurements on the same turbines enabled a thorough validation of the simulations. Generally a very good agreement was observed between experimental and simulated results, not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position. The deviation between predicted and measured overall sound levels (as a function of rotor power) was less than 1-2 dB for both turbines, which is smaller than the scatter in the experimental data. All in all, the present study provides a firm validation of the prediction method, which therefore is a valuable tool for the design of quiet wind turbines and for the planning of wind farms.

1 Introduction

Wind turbine noise is still one of the major hindrances for the widespread use of wind energy. The availability of fast and accurate wind turbine noise prediction methods is important for the design of quiet wind turbines and for the planning of wind farms. The present paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The availability of detailed acoustic array measurements on the same turbines provides a unique possibility to assess the predictions not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position.

The experimental results used in this study were obtained in the European SIROCCO project[1] which aims at a reduction of wind turbine noise by designing new blades with low trailing edge noise emissions. The project focused on two wind turbines: an 850 kW GAMESA turbine and a 2.3 MW GE turbine, with rotor diameters of 58 m and 94 m respectively. Acoustic field measurements were performed on both baseline turbines, to characterize the noise sources and to verify whether trailing edge noise from the blades was dominant. A large horizontal microphone array, positioned roughly one rotor diameter upwind from the turbine, was used to measure the distribution of the noise sources in the rotor plane and on the individual blades. A detailed description of the GAMESA measurements is given in Ref.2.

The simulations in this study are based on the trailing edge noise prediction code developed by Brooks, Pope, and Marcolini[3] ('BPM' code), which is incorporated in the wind turbine noise prediction code SILANT[4]. Based on boundary layer displacement thicknesses calculated with an airfoil design code, SILANT provides the radial noise source distribution on the blades. This radial source distribution is then extended with the effects of trailing edge noise directivity and convective (or Doppler) amplification, as a function of rotor azimuth and as perceived by an observer at a given position (in this case the position of the microphone array). Finally, in order to allow direct comparison to the measured array results, the calculated rotor noise source distribution is input to an array simulation code, to yield the simulated acoustic source maps.

The organization of this paper is as follows. First, Section 2 outlines the results of the acoustic field measurements on both turbines. Next, Section 3 describes the structure of the wind turbine noise prediction method. The experimental and simulated results are then compared in Section 4. Finally, the conclusions of this study are summarized in Section 5.

2 Field measurements

The acoustic measurements on both turbines were carried out using the same elliptically shaped array of 148 microphones, mounted on a horizontal wooden platform of about 16x18 m^2. The platform was positioned roughly one rotor diameter upwind from the turbine, resulting in a 'view angle' of about 45° (Figure 1). The 'misalignment angle' α is the angle between the rotor axis (depending on wind direction) and the line from turbine to array. Whereas the blades of the GE turbine were untreated, for the GAMESA rotor one blade was cleaned, one blade was tripped, and one blade was left untreated, in order to assess the effect of blade roughness due to e.g. dirt or insects. More details about the test set-up and data-acquisition and -processing procedures are given in Ref.2.

Figure 2 shows pictures of the test set-up in Spain (GAMESA) and The Netherlands (GE), with typical noise source distributions in the rotor plane (averaged over many revolutions). Note that these source maps correspond to the upwind measurement position on the ground, and that the colour scale is relative to the maximum level for each measurement. For both turbines it can be seen that, for an observer on the ground, most of the noise is produced by the outer part of the blades (but not the very tip), during their downward movement. As described in Ref.2, this source pattern, which causes the typical swishing noise during the passage of the blades, can be explained by trailing edge noise directivity and convective amplification. The GAMESA turbine also shows a minor noise source at the nacelle.
Interestingly, for some frequencies both turbines also showed small noise production when the blades pass the tower (see Figure 3 and Figure 5). The nature of this minor 'tower source' is hard to assess on the basis of the present data, but it could originate from (1) reflection of blade noise on the tower, (2) impingement of blade tip vortices on the tower, and/or (3) the upstream influence of the tower on the flow field around the blade.

3 Prediction method

Since the experiments indicated that trailing edge noise is the dominant noise source for both wind turbines, a prediction code was developed which calculates the blade trailing edge noise. The calculation can be split up into four steps:

1. The prediction code only needs the blade geometry and the turbine operating conditions (RPM, wind speed, and blade pitch angle) as input. First, the blade is divided into a number of radial segments (21 for the present cases). Next, the local Reynolds number and angle of attack are obtained from an aerodynamic wind turbine model, based on the blade element momentum theory. Then, the RFOIL airfoil design and analysis code[5] is used to calculate for each segment the trailing edge boundary layer displacement thicknesses on the pressure and suction side. RFOIL is an extension of XFOIL[6] and takes into account rotational effects.

2. The boundary layer thicknesses and Reynolds numbers are used as input for the BPM model[3], which is a 2D semi-empirical prediction code for trailing edge noise. This yields the blade noise spectra for the different radial segments of the blade.

3. Next, the effects of trailing edge noise directivity and convective amplification[2] (including the Doppler frequency shift) are applied to these radial source strengths (as a function of rotor azimuth), to obtain the effective noise source distribution in the rotor plane, as perceived by an observer at a specified position. For the present simulations the observer position was taken to be the position of the microphone array in the field tests.

4. Finally, the rotor noise source distribution is used as input for an array simulation with the same geometry and processing method as in the field tests[2]. In this way, simulated acoustic source maps are obtained, which can be directly compared to the measured maps. The rotor noise spectrum is then determined by applying a power integration method[7] to the simulated or measured source maps.

4 Comparison between simulation and experiment

In this section the simulations will be compared to the experimental results. This assessment will be made in terms of the noise source distribution in the rotor plane (Section 4.1), the rotor noise spectra (Section 4.2), and the overall noise levels as a function of rotor power (Section 4.3).

4.1 Noise source distribution in rotor plane

The measured and simulated source maps for both turbines are shown in Figure 3 to Figure 6. Note that these source maps correspond to the upwind measurement position on the ground. The range of the colour scale is always 12 dB, and the maximum is adjusted for each individual frequency band. The experimental source maps were averaged over all measurements, which were carried out for misalignment angles α (see Figure 1) around 0° and wind speeds (normalized to 10 m height) between 6 and 10 m/s. The simulations were done for a misalignment angle of 0° and a wind speed close to the average experimental wind speed.

In general a very good qualitative agreement is observed between experiments and simulations. As in the experiments, the simulated source maps show dominant noise radiation from the outer part of the blades, during their downward movement. Similar to the experiments, the source maximum shifts to a higher radius for increasing frequency, which can be attributed to the thinner trailing edge boundary layer at higher radius. In some cases even the minor side-lobes (e.g. around "11 o'clock" for 400-500 Hz in the GE results), which are an artefact of the array method, are reproduced in the simulations. Obviously, the minor experimental noise sources, at the nacelle and the tower, are not reproduced in the simulation, because these are not simulated in the trailing edge noise prediction model.

For the GAMESA turbine, the simulated source radius seems to be slightly higher than in the experiments. This may be due to the fact that the measured rotor had one tripped, one clean, and one untreated blade, while the simulations are done for clean blades. Tripping results in a thicker trailing edge boundary layer, so that the trailing edge noise at a given radius shifts to lower frequencies.

Whereas the previous results were obtained for misalignment angles around 0°, for the GE turbine measurements were also done for large misalignment angles. The measured and simulated source maps for these angles are shown in Figure 7. It can be seen that the location of the source region shifts upward or downward when the right- or left-hand side of the rotor plane is turned towards the array respectively. This can be qualitatively explained by the change in the component of the blade velocity in the direction of the array, which results in a change in convective amplification. At the high misalignment angles the array resolution decreases due to the oblique view angle. Again a good qualitative agreement between simulation and experiment is found, indicating that the changes in source pattern are well captured by the trailing edge noise prediction method. In the remainder of this paper all results will be for a misalignment angle of 0°.

4.2 Rotor noise spectra

As explained in Section 3, the source maps were quantified using a power integration method. Before comparing the simulated to the measured rotor noise spectra, first some intermediate results from the simulations are discussed. As an example, Figure 8 shows three rotor noise spectra from the GE simulations (the GAMESA results were similar): the 'BPM' spectrum (output of simulation step 2), the rotor spectrum after including directivity and convective effects (output of step 3), and the integrated rotor spectrum from the array simulation (output of step 4). Note that the sound levels PWL are *apparent* Sound Power Levels, because the measurements were only done for the upwind array position on the ground, rather than on a sphere around the turbine. By comparing the first two lines, it can be seen that directivity and convection result in a small shift of the spectrum to higher frequencies, because the blades are moving towards the observer on the ground when they produce most of their noise. Interestingly, the noise *level* is hardly affected: although directivity and convection yield a large asymmetry in the noise source distribution, the effect is rather small when averaged over all rotor azimuths.

By comparing the second and third line, it can be seen that the power integration method results in an underestimation of the actual rotor noise level. The difference is small at low frequencies, but increases to almost 5 dB at the highest frequency. This deviation is probably due to assumptions and simplifications in the power integration method, which are not completely true for the simulated source maps[8]. As a result, the power integration method underestimates the actual overall rotor source level by about 1 dB for the present simulation. Note that this effect occurs both for the simulated and the measured integrated rotor noise spectra.

The measured and simulated integrated rotor noise spectra for the GAMESA turbine are shown in Figure 9. These spectra correspond to the source maps presented in Figure 5 and Figure 6. As mentioned before, the experimental results were averaged over all measurements, and the simulations were done for a wind speed close to the average experimental wind speed. Since the GAMESA rotor had one tripped, one clean, and one untreated blade, while the simulations were done for a clean rotor, the experimental GAMESA spectrum was corrected on the basis of the individual blade noise spectra[2], to obtain the spectrum of a 'clean' rotor. For the measured source maps the hub region was excluded from the integration. Figure 9 shows a good agreement between the measured and simulated spectra, in terms of levels and spectral shapes. For the GE turbine, the simulated spectrum (Figure 8) showed the same level of agreement with the experimental spectrum. This good agreement between measured and predicted spectra for both turbines indicates that the prediction method captures the physics well.

4.3 Overall noise levels as a function of rotor power

In the previous section it was shown that the average experimental spectra for both turbines corresponded well to the simulations for the average experimental wind speed. Next, it was investigated if the simulations also accurately predict the dependence of the turbine noise on wind speed. Simulations were done for a range of wind speeds and the overall sound level was determined as the sum of the calculated rotor source distribution (output of simulation step 3). The experimental sound level was determined from the integrated rotor spectrum for all measurements, to which 2 dB was added for both turbines to account for the underestimation by the power integration method (see previous section) and coherence loss effects[9]: a comparison between overall integrated rotor levels and measured levels at the single array microphones (for the GE turbine) indeed showed an offset of 2 dB. In addition, on the basis of the individual blade noise spectra[2] 1.5 dB was subtracted from the overall levels of the GAMESA turbine, to account for the fact that the rotor had a tripped and untreated blade, while the simulations are for a clean rotor. In order to avoid disturbing effects from uncertainties in the measured nacelle wind speed, the sound levels were plotted as a function of the rotor power.

Figure 10 to Figure 12 show that for both turbines a good agreement is obtained between the predicted and measured overall levels. The dependence on rotor power is also well reproduced. For both turbines the difference between measurement and prediction is smaller than 1-2 dB, which is smaller than the scatter in the experimental data.

5 Conclusions

This paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The availability of detailed acoustic array measurements on the same turbines enabled a validation not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position.

The prediction code only needs the blade geometry and the turbine operating conditions as input. Based on boundary layer thicknesses calculated with an airfoil design code, a trailing edge noise prediction code provides the radial noise source distribution on the blades. After application of directivity and convective effects, the rotor noise source distribution is input to an array simulation code, to allow direct comparison to the measured source maps.

In general a very good agreement was observed between experiments and simulations. As in the measurements, the simulated source maps show dominant noise radiation from the outer part of the blades, during their downward movement. This source pattern, which causes the typical swishing noise during the passage of the blades, can be explained by trailing edge noise directivity and convective amplification. The source maximum shifts to a higher radius for increasing frequency, which can be attributed to the thinner trailing edge boundary layer. For high misalignment angles between array and turbine, the simulations show the same shift in source pattern as in the experiments. For both rotors a good agreement between the measured and simulated spectra was observed, in terms of levels and spectral shapes, which indicates that the prediction method captures the physics well. Moreover, the dependence of noise levels on rotor power was well reproduced: the deviation between predicted and measured overall sound levels was less than 1-2 dB for both turbines, which is smaller than the scatter in the experimental data.

All in all, the present study provides a firm validation of the prediction method, which therefore is a valuable tool for the design of quiet wind turbines and for the planning of wind farms. In a next step, it is planned to extend the prediction code to the calculation of noise footprints around a wind turbine as a function of rotor azimuth. This will allow an assessment of the locations where the highest noise levels are perceived, and where the noise level variations during one revolution (swishing) are largest.

Acknowledgments

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Figures

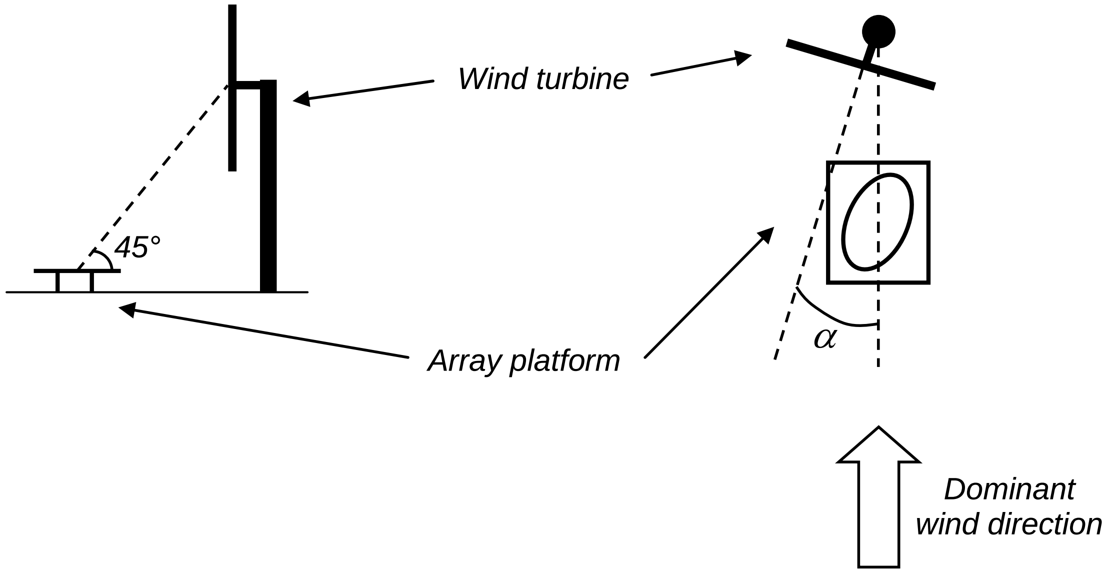

Figure 1: Side view (left) and top view (right) of test set-up.

Figure 2: GE 2.3 MW turbine (left) and GAMESA 850 kW turbine (right) with typical noise source distribution in the rotor plane.

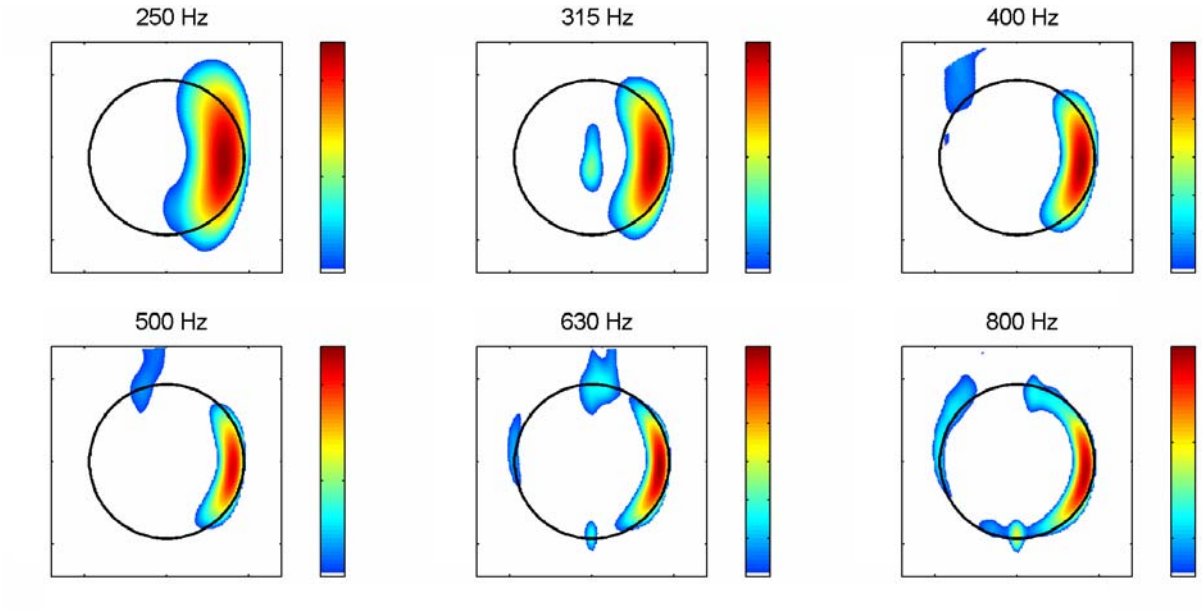

Figure 3: Measured source maps for the 2.3 MW GE turbine (the black circle indicates the 94 m rotor diameter). The method and plots generated are all relative data corresponding to only one configuration upstream of the rotor and detected hot spots within the dynamic range of the acoustic beamforming testing.

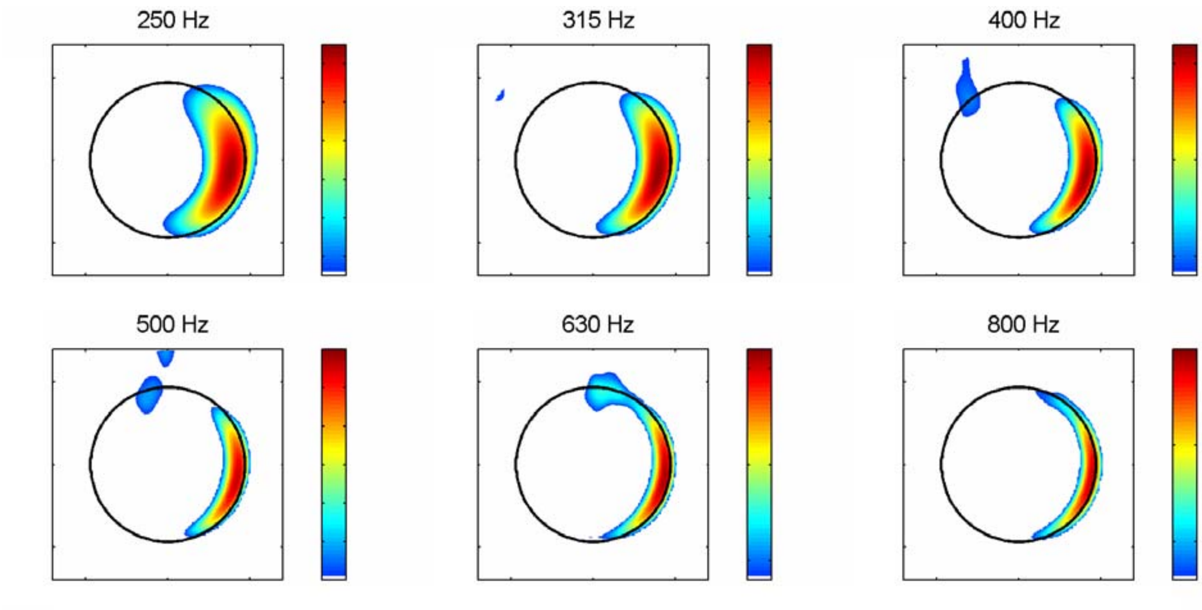

Figure 4: Simulated source maps for the 2.3 MW GE turbine (the black circle indicates the 94 m rotor diameter). The method and plots generated are all relative data corresponding to only one configuration upstream of the rotor and detected hot spots within the dynamic range of the acoustic beamforming testing.

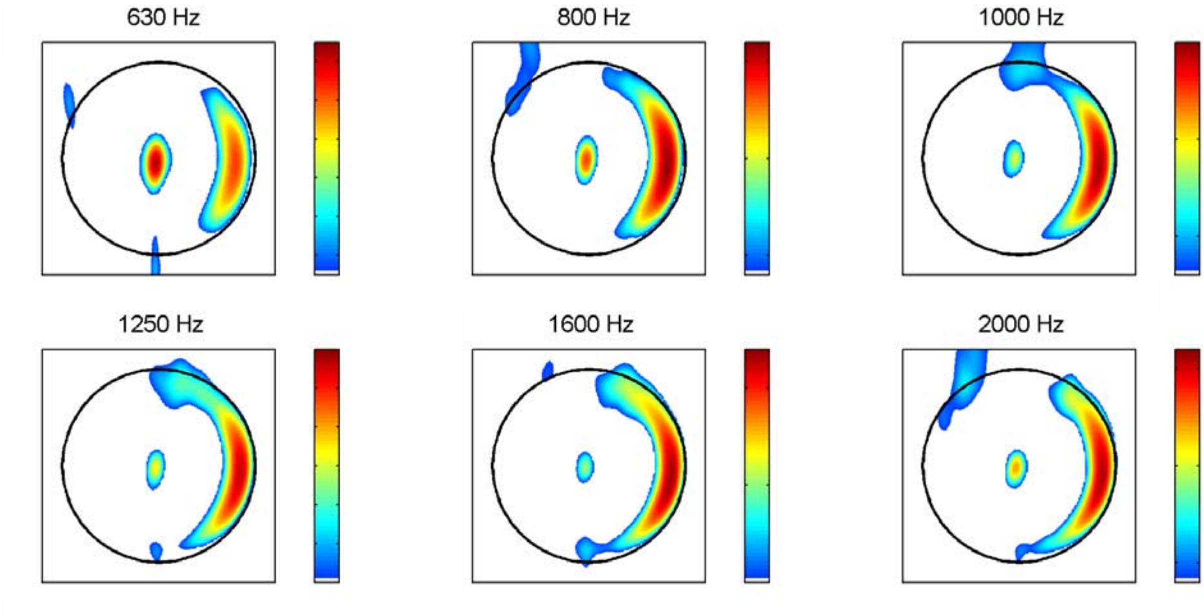

Figure 5: Measured source maps for the 850 kW GAMESA turbine (the black circle indicates the 58 m rotor diameter).

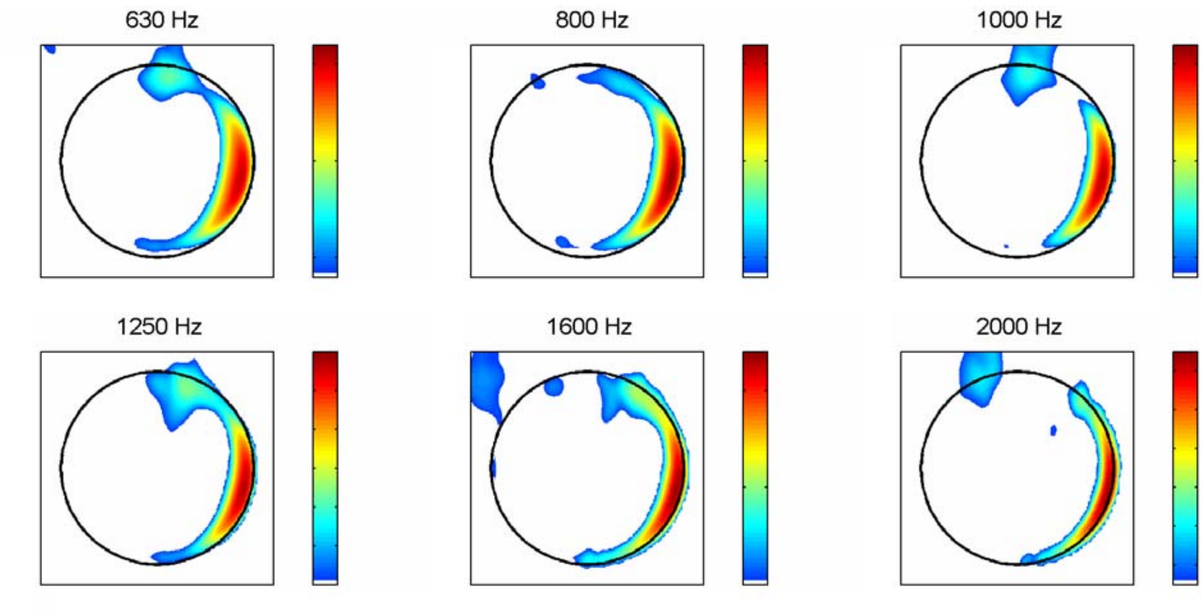

Figure 6: Simulated source maps for the 850 kW GAMESA turbine (the black circle indicates the 58 m rotor diameter).

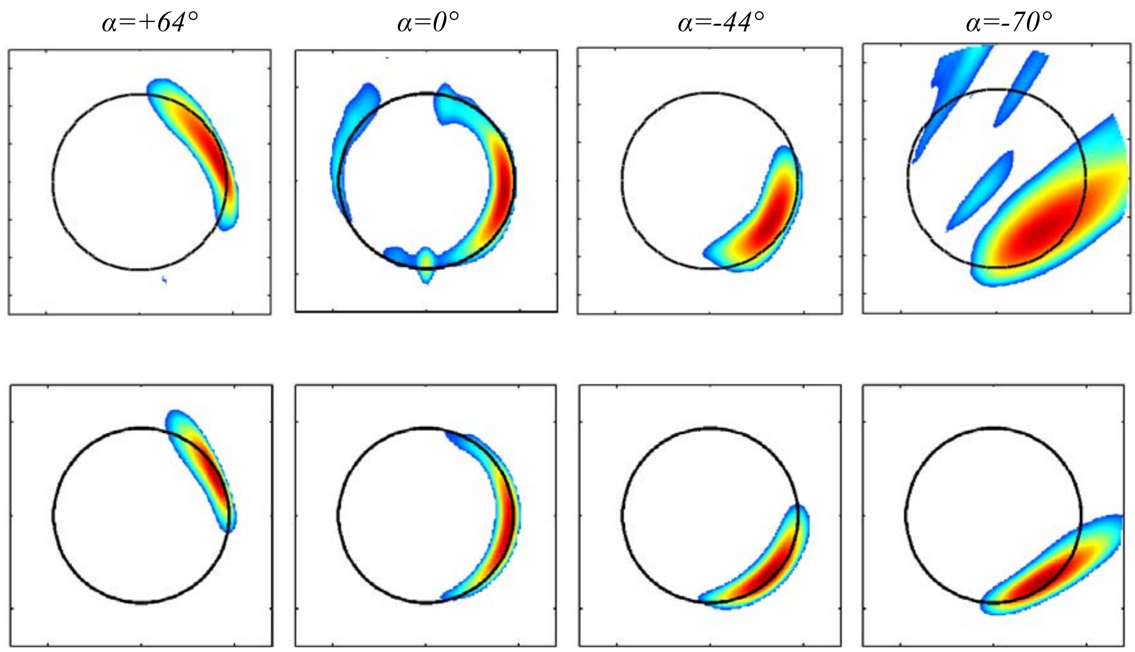

Figure 7: Measured (upper row) and simulated (lower row) source maps for GE turbine at different misalignment angles (800 Hz).

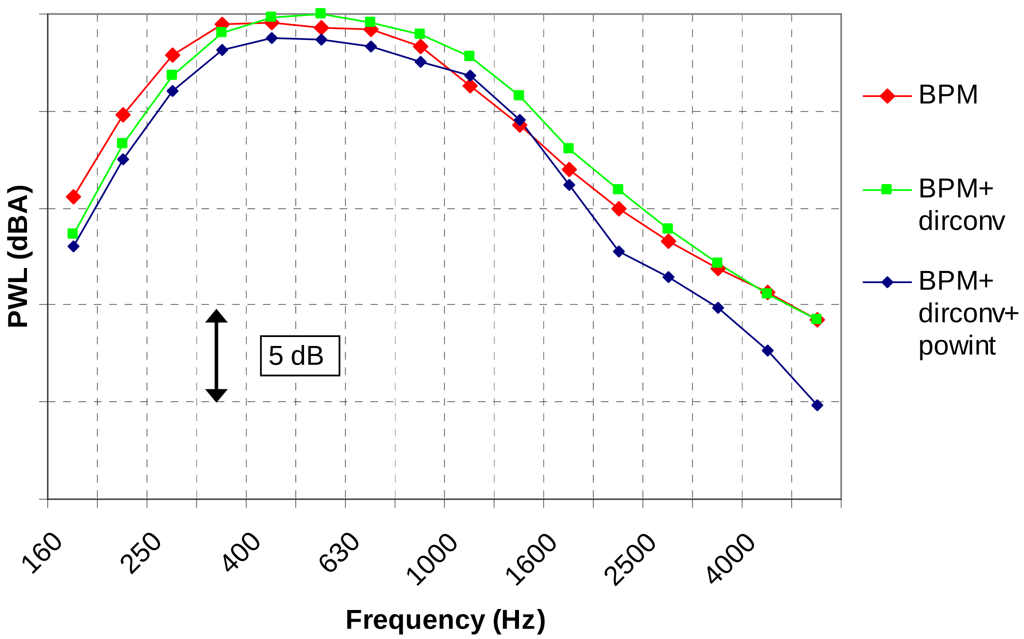

Figure 8: Intermediate rotor noise spectra from the simulation of the GE turbine.

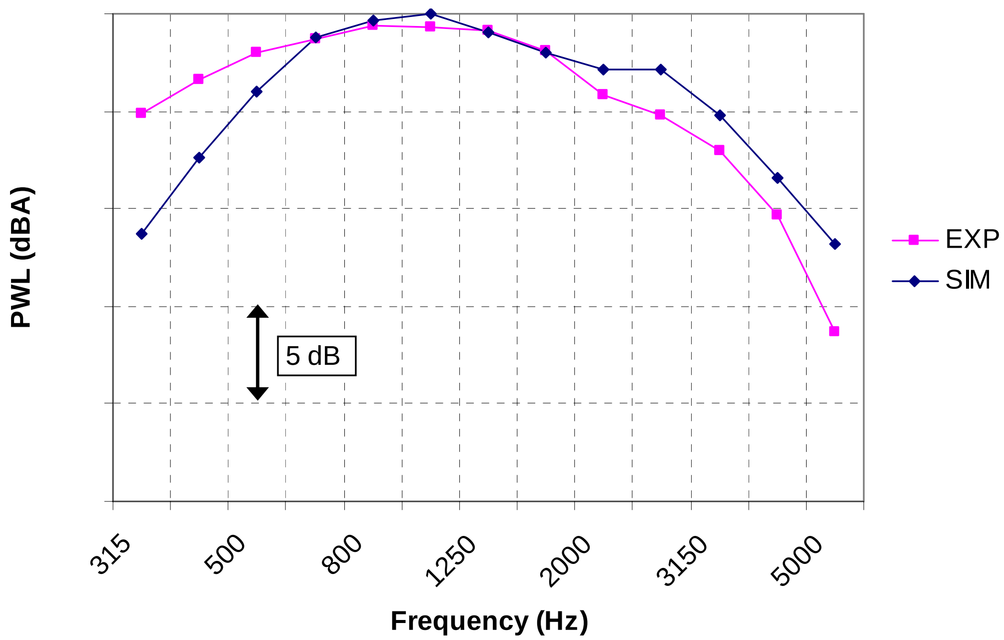

Figure 9: Measured and simulated GAMESA rotor noise spectra.

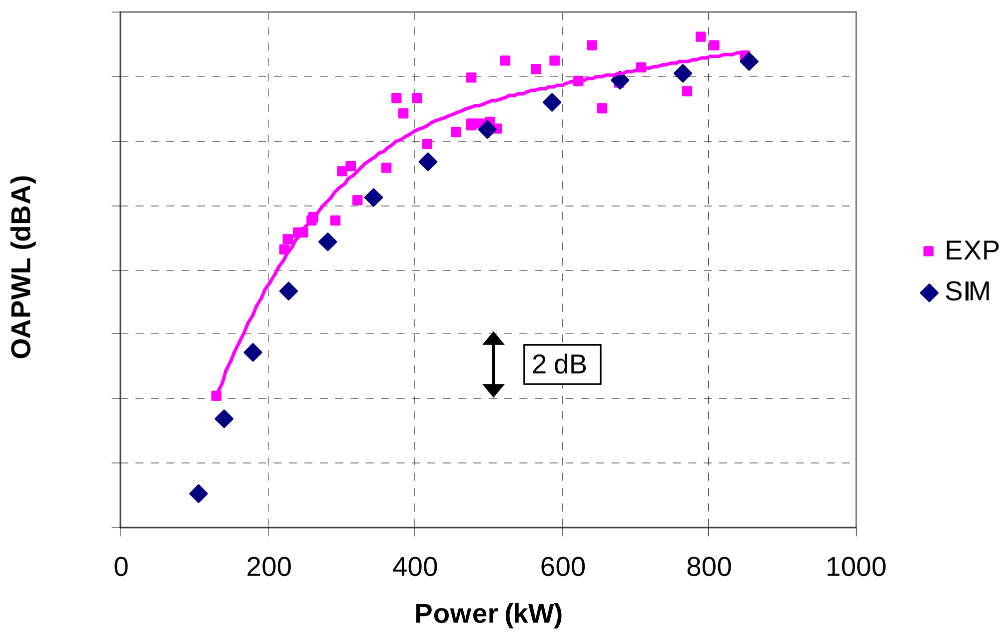

Figure 10: Measured and simulated overall rotor noise levels as a function of power for GAMESA turbine.

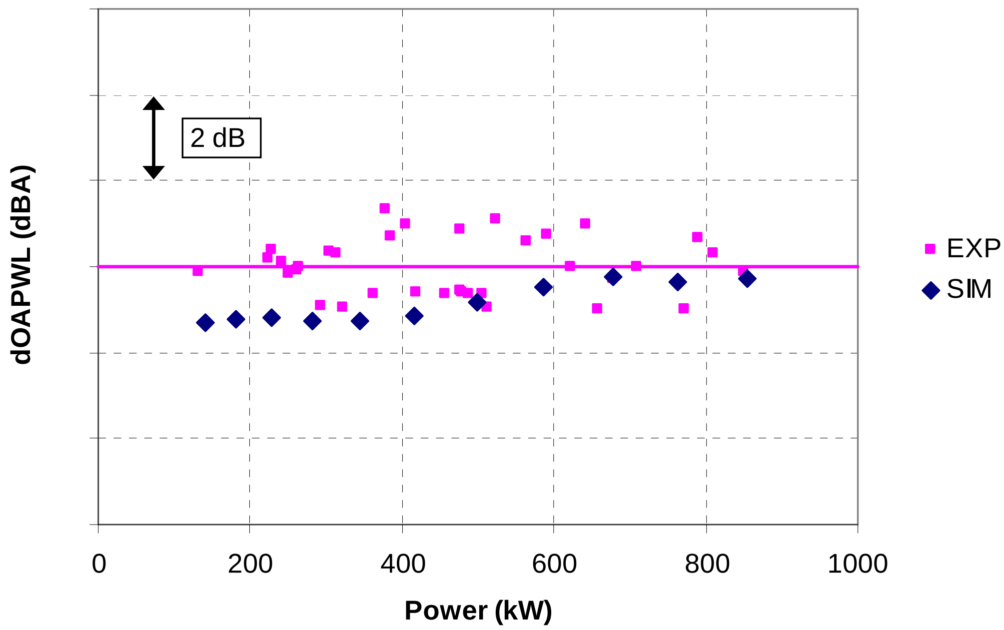

Figure 11: Deviation between measured and predicted overall noise level as a function of power for GAMESA turbine. The levels are normalized using a curve fit through the experimental data (see Figure 10).

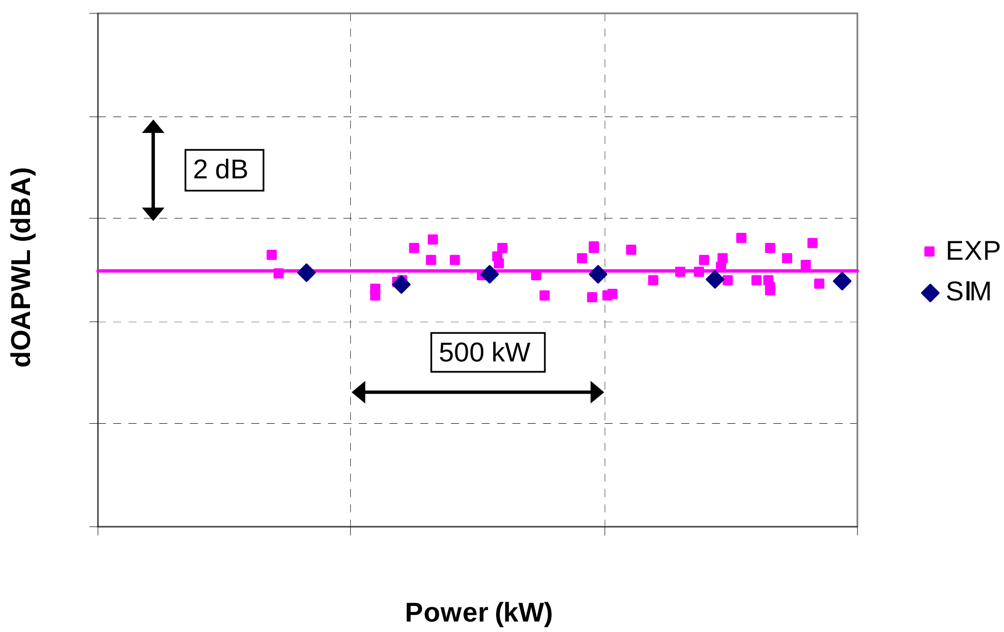

Figure 12: Deviation between measured and predicted overall noise level as a function of power for GE turbine. The levels are normalized using a curve fit through the experimental data.