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TONAL NOISE MITIGATION ON WIND TURBINES

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Free layer damping tiles were applied to the tower of a wind turbine, whose problematic tone of ~350 Hz was amplified by resonant vibrations of the tower. IEC 61400 measurements before and after the installation of the damping tiles showed that the audibility of the problematic tone was reduced by 3 dB and a broadband noise reduction of 3 dB was also observed.
Several steps were carried out to determine that free layer damping was a suitable solution for this wind turbine. Firstly, acoustic and vibration surveys were carried out to ensure that the problematic tone was, indeed, amplified by the tower. Secondly, as a means of de-risking the application of the solution, structural-acoustic finite element models were created. These were used to predict the modal shape of the tower and consequently to determine the number and placement of tiles necessary to reduce the tone. After the installation of the tiles on the tower, acoustic and vibration measurements were carried out to determine their effectiveness on both reducing the amplitude of the resonant vibrations of the tower and the tonal and broadband noise of the turbine.
Keywords: Tonality, Mitigation, Wind turbine, Free layer damping

1. Introduction

Tones are very easily perceived by human hearing, so that tonal noise from wind turbines seems to increase the annoyance of receivers and has been identified as the primary cause for complaint [1]. Consequently, legislation has been put into place to regulate tonal noise emitted from wind turbines, which, if not adhered to can lead to financial penalties, curtailment and even closure of a turbine site. The risk of such economic losses has highly motivated the wind turbine industry to develop solutions to tonal noise.

A tonal noise mitigation solution has been developed based on free layer damping of the wind turbine tower. This paper presents a case study where vibration measurement combined with finite element (FE) modelling showed that the principal radiation source of tonal noise was the tower wall. Polymer tiles were adhered to the walls of the wind turbine tower, thereby increasing their damping characteristics. This free layer damping solution reduced the amplitude of resonant vibrations responsible for amplifying tonal noise. A validation IEC 61400 measurement showed that the audibility of the tone was significantly reduced, and that the installation also lead to a broadband sound power level reduction.

2. Technical Background

2.1 Sources for and propagation of tonal noise produced by wind turbines

Tonal noise in wind turbines is commonly caused by vibrations produced by the rotating components of the drivetrain. For example, vibration can be caused through the interlocking of gear teeth in the gearbox referred to as gear meshing. These vibrations, while causing tonal noise, [2] may not necessarily be problematic, as the drivetrain is often a considerable distance away from the nearest receiver. However, if the frequency of vibration is closely aligned with structural resonant frequencies of the tower, then the tower's modal response can be excited, therefore amplifying and radiating tonal noise. Wind turbine towers are commonly lightly damped steel structures with very large surface areas, making them extremely efficient radiation surfaces for tonal noise. It should be noted that tonal noise can also be caused by the blades; however, in the present paper only tonal noise that is amplified by the tower shall be addressed.

2.2 Tonal mitigation solutions

Tonal noise from wind turbines can be mitigated by either reducing the vibrations of the source or modifying the propagation of the noise to the receiver. Reducing the vibrations of the source can be achieved by exchanging the gearbox or other drivetrain components or setting the operating system to avoid frequency matching with the modal response of the tower. While these solutions can be very effective, they are likely to be impractical and involve significant economic investment or financial losses.

There are several ways to modify the noise propagation from the turbine through the air to the receiver. This can be achieved by modifying the noise propagation through the air, for example, by restricting the turbine to operate in specific wind directions or placing acoustic barriers close to the receivers. As these solutions are also likely to be impractical and connected to significant economic losses, this paper shall focus on mitigation solutions where the propagation from the source, through the tower, i.e. the structural propagation through the tower, is modified. In particular, this is achieved by damping the tower walls, especially their modal response, so that tower wall surfaces will radiate vibration through the air, which is perceived as noise by the receiver.

There are different mechanisms for damping the tower walls. One example is through the installation of a tuned mass damper (TMD) or multiple tuned mass dampers (MTMD), which are designed to reduce the vibration amplitude at the frequency they are tuned to or a range of frequencies about the tuning frequency. This is achieved by creating one (or two) new frequencies that have a higher or lower frequency than the frequency for which they are tuned [3]. Consequently, they are not broadband dampers. However, for turbines with a variable running speed this can lead to new resonances being excited and, hence, tonal noise simply being shifted to different frequencies. For turbines with a variable running speed it is, therefore, better to install a broadband damper. Examples of broadband dampers that can be applied to wind turbines are free layer damping, constrained layer damping and advanced particle damping (APD) [4]. Free layer damping is the focus of this paper and is discussed in depth below. Constrained layer damping involves the adhesion of one or more layers of damping material (commonly a polymer) to the tower wall and a rigid layer (commonly steel) adhered outside the polymer. For constrained layer damping vibration energy is dissipated via heating as the polymer layer is forced to shear between the two rigid surfaces [5]. APD involves polymer particles within a container, where vibration energy is dissipated via friction between particles and via their internal deformation [5]. An advantage of APD is that containers can be constructed with magnetic attachments that allow their installation within a wind turbine without adhesives. For narrow turbine towers a layer solution maybe more practical than the APD pods as the containers have a longer depth than the thickness of the tiles.

2.3 Free layer damping

Free layer damping is very similar to constrained layer damping. However, for free layer damping (sometimes also called extensional damping) typically only a single layer of damping material is attached with a strong bonding agent to the surface of a structure. As the damping material extends and compresses due to the flexural stress of the underlying structure, energy is dissipated. Thus damping tiles are most effective when placed on areas with high displacement. The effectiveness of the damping also depends on the thickness and composition of the damping material layer.

In order to protect the damping material tiles from being exposed to the elements, they should to be applied on the inside of the tower. This complicates the installation of the layers as fumes from the bonding agent may be released into a confined space.

However, as free layer damping involves less material than constraint layer damping, costs are reduced. Furthermore, the damping provided through the single layer may be enough to reduce the tonal noise sufficiently to the desired levels. For these reasons the free layer damping solution was chosen to be implemented.

3. Methodology

A case study of a turbine that operates at two fixed speeds depending on the wind speed is presented. Several steps involving vibration and acoustic surveys on and FE modelling of this turbine were used to determine that free layer damping was a suitable solution for reducing the audibility of tonal noise. Finally, after the installation of the free layer damping tiles further acoustic and vibration surveys were conducted to quantify the reduction in the tower vibration and, hence, the tones in the field.

Vibration measurements were used to determine vibration pathways and to determine if the measured tones were related to tower resonances. A concurrent acoustic survey was conducted. Note the acoustic measurements, calculation of the sound power level and the reporting of the tones were done in accordance with the IEC 61400-11. The surveys also showed that the problematic tones occurred for low wind speeds, when the turbine was operating at a lower fixed speed; hence results for the turbine operating in the higher fixed speed are not presented.

As the vibration and acoustic survey showed that high levels of excitation of the tower levels correlated with the problematic tones, it was determined that damping the tower walls could reduce tonal noise. A broadband damping solution was desirable, as tones were noted for the turbine operating at the low and high fixed speed, albeit with the tones not being problematic when the turbine operated in the higher fixed speed. Thus, applying a TMD solution was eliminated, leaving the APD pod solution and a damping layer solution as possible candidates. As the tower had a maximum diameter of 2 m, the installation of APD pod solution was less practical due to the depth of the container. For a commercial reasons the free layer damping solution was chosen to be installed instead of the constrained layer damping solution.

To de-risk the process of installing the solution by ensuring that the reduction of tones is possible, an FE model was created. A structural-acoustic model of the existing turbine was created in COMSOL Multiphysics and calibrated with the measured data. In particular, a 3D model of the turbine was created with the tower sections, blades and nacelle walls modelled as shell elements and the drivetrain components as solid elements. The model was excited using force related gear meshing, with the turbine being fixed to the ground. The tower was modelled to be steel, and the blades and nacelle walls as fibreglass composite. The material properties of the drivetrain components were modelled such that modelled properties reflected the properties of the turbine.

The purpose of the model was primarily to determine the modal shape of the tower at the problematic frequency, as damping tiles are most effective when being placed on areas of with a high displacement. The model predicted that areas of high displacement for this turbine were located at the bottom of the tower. Having determined its modal shape, models were developed to quantify the effect of placing damping tiles on the tower walls. In particular, the damping tiles were modelled to be part of the tower shells with modified material properties determined through sub-modelling. Thus several different coverage strategies of the tower walls with damping tiles were modelled, including a coverage of the bottom section, the bottom and top section, and a full coverage, and the sound pressure level predicted was predicted.

After the installation of the damping tiles, a survey was conducted to determine the vibration and tonal reductions and if the solution reduced the tonal audibility to the desired values. To allow for a comparison with the results before the installation the acoustic survey was also done in accordance to the IEC 61400-11 standard.

4. Results

4.1 Initial acoustic and vibration survey

An initial acoustic survey conducted according to the IEC 61400-11 standard showed that the turbine had a several problematic tones, including the worst near 350 Hz and its harmonic near 700 Hz. This tone is shown in the top figure in Figure **1**, which shows the unscaled power spectral density of audio signal. This frequency correlates with one of the gear meshing frequencies and a prominent peak in the vibration spectra recorded the bottom of the tower (middle and bottom figures in Figure **1**). Based on these correlations, it was determined that the 350 Hz tone was generated by gear meshing, transmitted into the tower and subsequently radiated into the air. The gear meshing frequency was calculated from the rotational speed and the number of gear teeth. Thus, it was concluded that a tower damping solution is likely to be very effective in reducing the audibility of the tone.

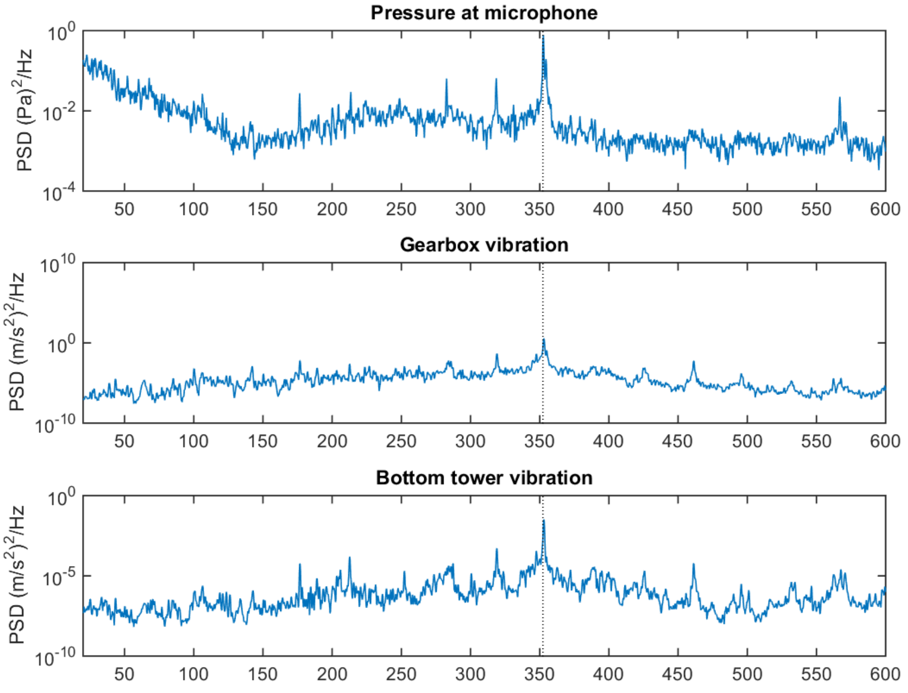

Figure 1: Tone at approximately 350 Hz. This frequency is related to one of the gear meshing frequencies, resulting in high levels of vibration of the gearbox. At this frequency high levels of vibration can also be observed at the bottom of the tower.

4.2 Finite element model

The finite element model was created to predict the modal response of the tower and the sound pressure level at the IEC position that is the observer position on the ground downwind from the turbine at a distance of tip height. Mitigated solutions where damping tiles were placed on different sections of the tower were also modelled to predict if the solution would be effective in the field.

Figure **2** shows the predictions for the turbine with and without mitigation solutions of the structural FE model of the normal acceleration of the tower at 353 Hz, which is representative of the problematic frequency observed in the initial acoustic and vibration survey. It shows that for this frequency the modal shape of the tower is such that the bottom section of the tower has the highest acceleration and will therefore amplify the problematic tone the most. This indicates that in order to effectively mitigate the tone, the damping tiles should be installed on the bottom sections of the tower.

Free layer damping is most effective when the tile coverage is greater or equal to the wave length of the modal shape (i.e. twice the distance between nodes). The FE model was used to determine that the spatial wavelength of the 350 Hz vibration was ~ 1 m (Fig. 2). Free layer damping tiles were therefore designed such that the continuous coverage on each turbine tower panel exceeded 1 m.

To determine if the tiles would be effective at decreasing the tonal noise, several mitigation solutions were modelled, namely covering the bottom, the top and the bottom and the complete tower with damping tiles. The model predicted that for frequencies between 100 and 600 Hz all the mitigation solutions applied to turbine would be effective at reducing the problematic tone (Fig. 2). For commercial reasons it was decided to install damping tiles covering the bottom and the middle section of the tower.

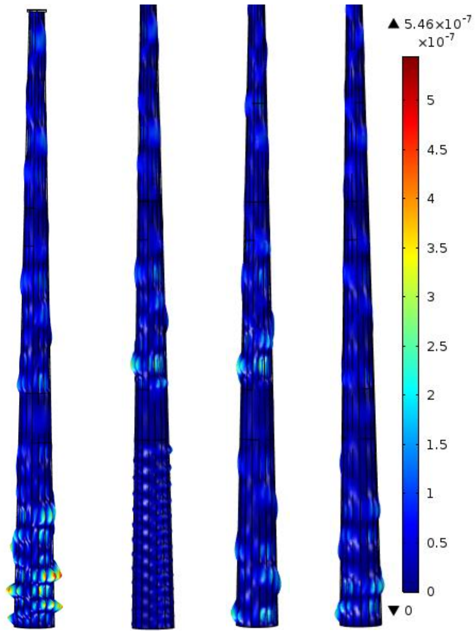

Figure 2: Predicted normal acceleration of the tower at 353 Hz for native turbine (left), turbine with damping tiles applied on the lower sections (2nd from left), turbine with damping tiles applied on the lower and top sections (2nd from right)), turbine with damping tiles applied across the whole tower (right). For the native turbine, the highest acceleration occurs in the bottom section of the tower.

4.3 Acoustic and vibration verification survey

After the installation of the damping tiles, a second measurement campaign was conducted. The results of these acoustic and vibration measurements of the mitigated turbine were compared to the results from the measurements prior to the installation free layer damping tiles. The aim of this comparison was to determine the effectiveness of the damping tiles and their ability to reduce the modal response of the tower wall and the related sound power level and audibility of tonal noise.

Figure 3 gives a representative example of the response of the native and mitigated towers after being excited with an impact hammer. The dotted line represents the problematic frequency (approx. 350 Hz) for which the tower was damped. It also shows that the damping is not only effective for the problematic frequency, but also for most frequencies between 200 and 600 Hz. In particular, it shows that the free layer damping material is indeed effective over a broad range of frequencies.

The acoustic output of the native and mitigated turbines were measured in accordance with the IEC 61400-11 standard. Comparing the audibility of the tonal noise before and after the installation of the damping tiles shows that the audibility of tonal noise was significantly reduced after the installation (Fig. 4). An example of a comparison between the audibility of tones for the native and mitigated turbine is shown in Figure 4 for the 9 m/s wind speed bin; all wind speeds are extrapolated to hub height. The black dashed lines denote the audible tone threshold (0 dB) and the threshold for when to report a tone (-3 dB). The most audible tone, with an audibility of approx. 6.9 dB for the native turbine, at approximately 350 Hz is reduced to 4.0 dB; the other audible tone at approximately 700 Hz is also significantly reduced by 5.5 dB. Figure **4** shows that the application of the damping tiles not only reduces the audibility of the tone at 350 Hz, but also reduce all other tones in the 100 to 700 Hz range to inaudible (Fig. 4). Furthermore, the tones at 3150 Hz and 3300 Hz detected for the native turbine were not detectable when the mitigated turbine was measured (Fig. 4). Note, although not shown here, the most prominent tone at 350 Hz was reduced by approximately 3 dB across all wind speed bins.

The reduction in tonal noise audibility was accompanied by a commensurate reduction in broadband noise. The broadband sound power level of the mitigated turbine was reduced by ~3 dB across all wind speed bins measured (Figure **5**). Note, for the mitigated turbine only wind speed bins between 6 m/s and 10 m/s were measured.

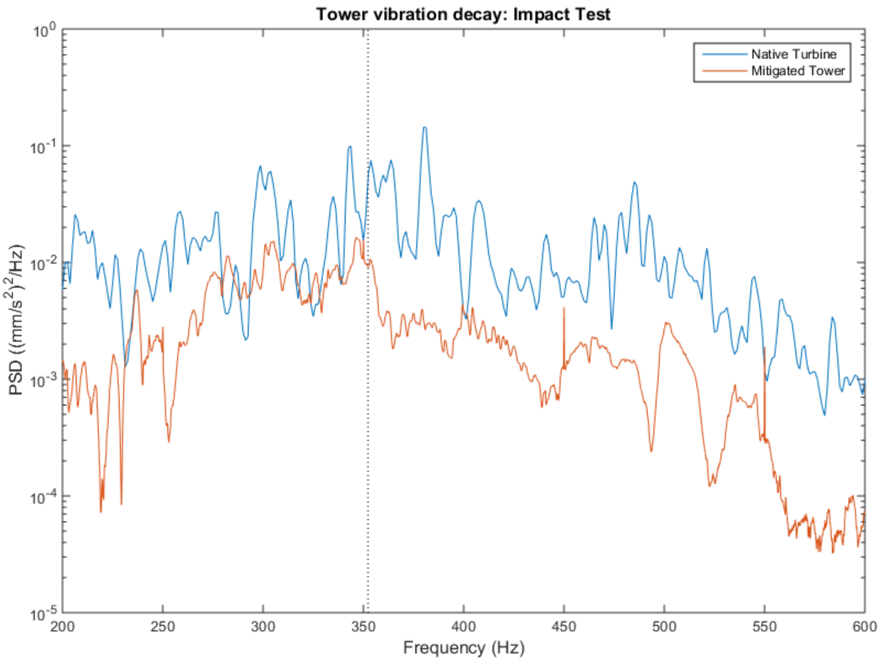

Figure 3: Power spectral density of the bottom of the native and mitigated tower after being excited by an impact hammer. The dotted line represents the problematic frequency for which the tower was damped.

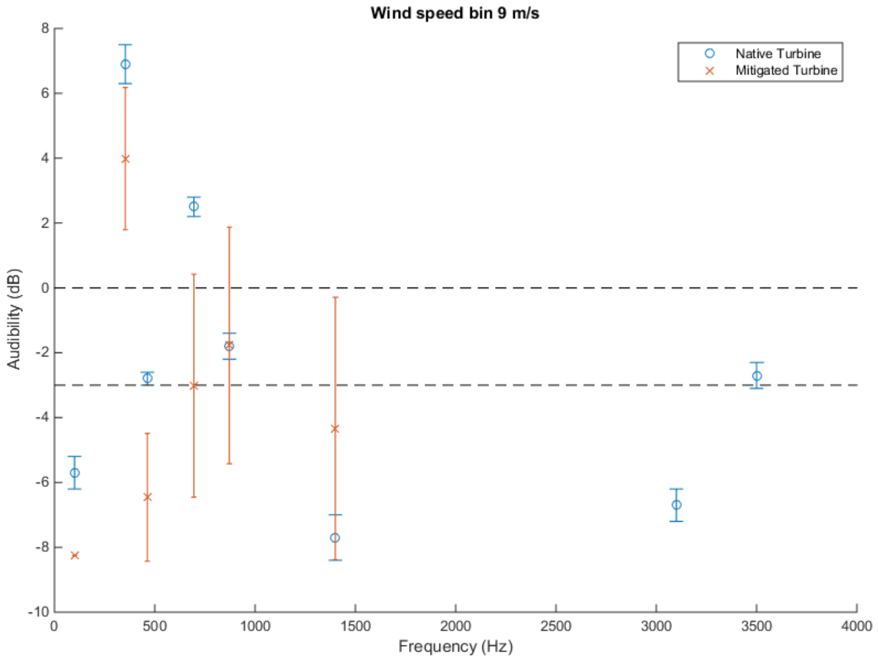

Figure 4: Tonal audibility as a function of frequency for the 9m/s wind speed bin (extrapolated to hub height).

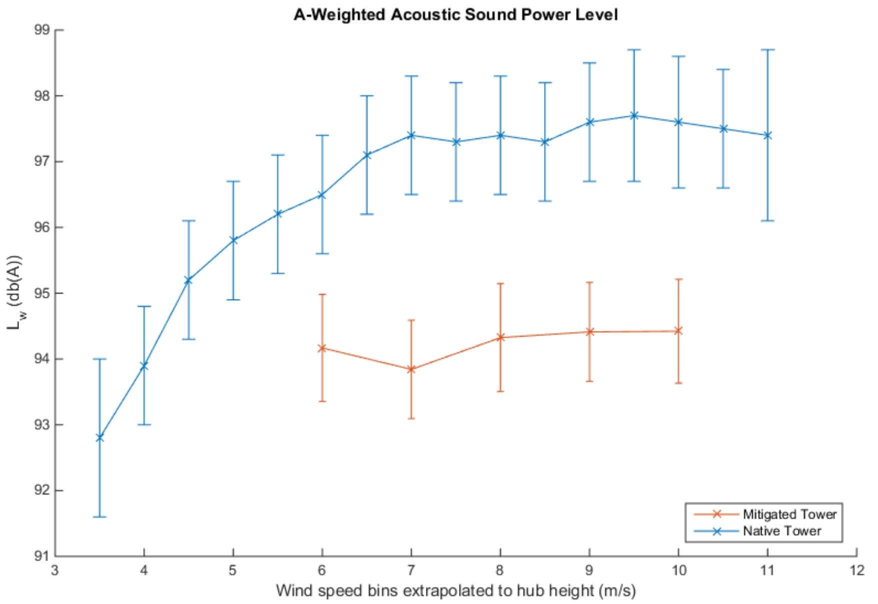

Figure 5: A-weighted sound power level as a function of wind speed bin (extrapolated to hub height) for the mitigated and native turbine.

5. Discussion

The coverage of the tower with damping tiles is related to the tonal audibility reduction. The greater the area covered by the damping tiles the greater the tonal audibility reduction. Thus damping tiles can be installed stepwise. Should further reductions be required, additional tiles could be installed or the free layer damping could be modified into a constrained layer damping solution by applying metal layers onto the polymer tiles.

The effectiveness of the present solution is limited to turbines for which the tones are amplified by tower resonances. In cases when the tonal noise is not amplified by tower resonances, but for example by the blades, the tower wall mitigation is likely to be not effective.

6. Conclusion

A case study of the wind turbine was presented which outlined how initial acoustic and vibration surveys together with FE modelling were used to predict that free layer damping could be an effective solution to reduce the tonal audibility of the wind turbine.

After the installation of damping tiles on the tower of the turbine, acoustic and vibration measurements demonstrated that the mitigation was successful. In particular, an average tonal audibility reduction of 3 dB was found in the field for the most prominent tone and resulting in a broadband noise reduction also of 3 dB. Results of the vibration survey found that tiles decrease vibration levels over a broadband range of frequencies (approx. 200-600 Hz) and, therefore, could be used for many tonal noise problems, especially for tonal wind turbines with a variable running speed.

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