Wind Turbine Noise Attenuation Using Modal Structural Damping

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ABSTRACT

Wind turbine towers can often become modal if matched closely in frequency with the excitation associated with rotating components in the drive train, such as gearboxes and generators. When these conditions are met, the modal response is greatly amplified due to the very low structural damping of the steel structure resulting in undesired audible tones. Furthermore, the steel structures have large surface areas making them very efficient at radiating tonal noise. Tonal noise can have adverse effects on neighboring residences and its emission can result in strong regulatory penalties.

It can be shown that the addition of damping to the turbine tower will significantly reduce the far-field tonal level. These results were achieved by using an innovative advance particle damping (APD) technology called EniDamp™. Experimental investigations on the dynamic and damping properties of the APD material were used to inform finite element models of a wind turbine with and without the pods filled with APD material.

Keywords: Wind turbine, Tonal noise, Mitigation I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Tonal noise emission by onshore wind turbines can adversely impact neighboring residential communities leading to loss of sleep, stress and related health problems (1). For these reasons tonal noise incurs strict regulatory penalties which may include running speed restrictions, night time curtailment and, in some cases, the complete closure of wind turbines (2-4) leading to considerable financial losses. Wind turbine manufacturers and operators are therefore highly motived to mitigate tonal noise that is emitted by any turbines within their fleet that emit tonal noise.

Typically, tonal issues become apparent after the wind turbines have been deployed. A retrofittable solution is therefore required to allow wind turbine operation that is in harmony with local communities. The authors present a new broadband damping approach where containers filled with EniDamp™, an Advance Particle Damping (APD) material, are fixed to wind turbine towers to increase their damping characteristics and thereby reduce tonal noise emissions. The broadband nature of the APD material is particularly suited for variable speed wind turbines, where the frequency of the tonal noise can vary over large ranges making other mitigation techniques, such as tuned mass dampers, inappropriate. Lab-based vibration experiments have been used to determine the dynamic and damping properties of the APD material. A phenomenological approach was used to incorporate these data in a numerical model using finite element (FE) methods to predict changes in tonality when pods with APD material, henceforth referred to as APD pods, are attached to a wind turbine tower.

2. TECHNICAL BACKGROUND

2.1 Tonal Noise Produced By Wind Turbines

Noise from wind turbines has two main sources: mechanical noise associated with components in the drive train which tends to be tonal in nature, and aerodynamic noise associated with blades slicing through the air, which tends to produce a broadband frequency range (5). Mechanical vibrations in the drive trains of wind turbines are created by imbalances of the rotating components, the teeth in the gearbox coming into contact with each other (referred to as gear meshing), and electro-magnetic (E-M) interaction between the spinning poles and stationary stators in the generator. Each of these vibration sources occurs in discrete frequency bands related to the rotation speed of each component: the

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vibrations and resultant noise therefore tend to be tonal. Rotational imbalances tend to occur at very low frequencies (< 20 Hz) below the audible range of human hearing. Conversely, gear meshing and E-M interactions tend to occur at low to moderate frequencies (50 Hz to 2 kHz) and are therefore most likely to produce tonal noise that impacts humans.

Drive train vibration becomes problematic when it excites resonances of large surfaces in contact with the air such as the tower, blades and nacelle walls, which the authors refer to as radiating surfaces. Gearbox and generator vibration can move through mounting systems and the drive shafts to the radiating surfaces. In instances where the discrete frequency produced by the gearbox or generator match those of resonances in the blades or tower, tonal noise is amplified and radiated. These radiating surfaces, especially tubular steel towers, tend to have very poor damping characteristics and are therefore readily excited by vibration and extremely effective at amplifying tonal noise.

Large megawatt scale wind turbines are commonly variable speed devices where the rotor speed varies between ~5 and ~20 rpm. The rotation speed of drive train components and related vibration also vary over a wide range as the rotor changes speeds to accommodate different wind conditions. The frequency of discrete mechanical vibrations will also vary and may run through one or more resonant frequencies resulting in the production of tonal noise with an intermittent nature (i.e. tonality may only occur at particular wind speeds).

Several mitigations methods have been used to reduce or remove tonal noise from wind turbines. In the case of variable speed turbines with intermittent tonality a control-approach can be used, where the rotor speed is limited to avoid frequencies which produce tonal noise. The use of such a control-approach however results in the wind turbine not running optimally and the loss of electricity yield. In cases where the tower can be shown to be the radiating surface, the lightly damped nature of the steel means that tonality can be mitigated by reducing the Q-factor of the structure. This approach has been exploited using constrained layer damping (6) to damp the tower. Retrofitting constrained layer damping to existing wind turbines however can be challenging as it requires rope access engineers working in confined spaces with chemical adhesives. Tuned mass dampers (TMD) may be useful for mitigating the resonances that amplify tonal noise, however their narrowband nature may not be appropriate for variable speed turbines and may actually amplify tonal noise at certain frequencies. The authors here propose a new broadband approach using advanced particle damping.

2.2 APD Broadband Damping: How it Works

Advanced particle damping (APD) media is a custom granulated elastomer of various sizes and materials. This media can be housed in a soft-shell or hard-shell container and applied to a vibrating structure for the purpose of damping structural vibration modes.

Prior work (7) to characterize APD has shown that altering the makeup of APD can result in a broadband damping performance. Various APD materials are used having different stiffness properties. The granules have a rough and irregular construction and finish, and granulated sizes are randomized.

As shown in Figure 1, APD is effective through two types of damping characteristics. At lower levels of input excitation, the inherent material damping properties are the dominant mechanism for attenuation. At higher input levels, the particle interactions become more dominant as they begin to move relative to one another. This results in a media that is not only effective at various levels of excitation, but also across a broad frequency spectrum.

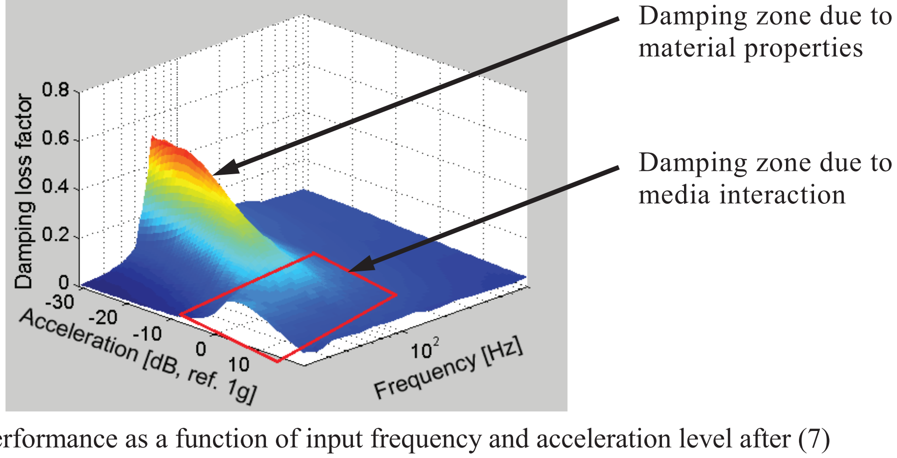

Figure 1 – Damping performance as a function of input frequency and acceleration level after (7)

Since APD is manufactured with elastomeric materials, the inherent structural properties, such as damping ratio and Young's modulus, are compounded to optimize performance. Materials with high levels of damping will absorb higher energy than that of lower damped compounds. Caution is exercised for adding too much damping in the elastomeric materials since there is also a desire to create motion and interaction between particles.

Control over the stiffness properties of the elastomer particles will affect how they respond to the input. Various elastomer hardness, or stiffness's, are used for the purpose of creating individual spring elements within the APD mixture. This results in a randomized body of tuned mass dampers, which will respond over a wide frequency range.

The APD granules are manufactured within a range of specific sizes though screen filtering. The various particle sizes contribute to the broadband performance. The assorted masses, which act on the various spring elements discussed above, help to broaden the range of effectiveness. Alternatively, independent particles masses will respond differently to the level of base excitation, furthering the range at which the media will be effective.

The APD granules are manufactured with rough and textured surfaces. The interaction between particles with rough surfaces creates higher damping levels than that of typical spherical bead damping media with smooth surface conditions. The irregular shapes of the APD media also result in higher number of contact points and interacting surface areas between particles than spherical media. A container of spherical particles can only make 'point' contacts with adjacent spheres, as opposed to ADP's irregular particles which can make 'surface area' contacts in addition to 'point' contacts. Once more, the number of contact points between spherical elements is fixed where APD has the possibility of increased contact points with adjacent particles. The effectiveness of APD is related to the attached structures mass and mobility, which will drive the amount of APD needed to achieve the desired damping. Structures with low mass and high mobility requires less APD media than heavy structures with low mobility.

3. EXPERIMENTS

3.1 Experimental Set-up

To quantify the effects of APD pods placed on the tower of a wind turbine and to determine the values of structural parameters that can be used in a FE model, simpler and more controlled experiments were conducted. In experiments aiming to predict the effect of placing APD pods on the tower, a flat 1 m × 1 m industrial steel plate, which was 12 mm thick, was suspended. A force was applied to the plate by a shaker whose output frequency was increased from 80 Hz to 600 Hz in steps of 2 Hz. For experiments aiming to determine the values of the structural parameters the shaker's output frequency was controlled by a white noise signal that resulted in all resonances of the plate being excited simultaneously. The normal surface acceleration was measured at 12 evenly distributed sensor locations. In order to determine the effect of placing APD pods on the steel plate experiments were run, where a single APD pod was placed in the center of the plate. Figure 2 shows the set-up of the steel plate with the APD pod attached.

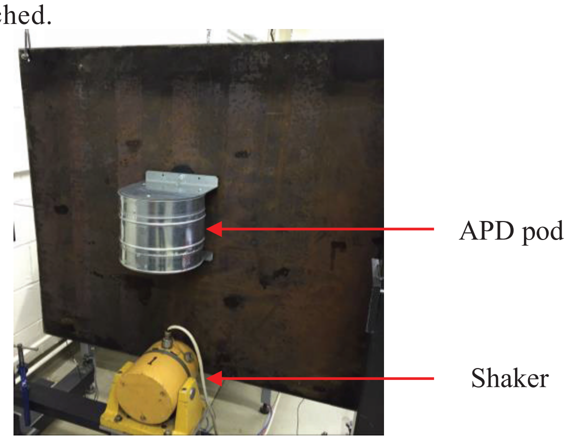

Figure 2 – Experimental set-up of the suspended plate with the APD pod placed in the center and the shaker.

The acceleration was measured at 12 evenly distributed sensor locations on the other side of the plate.

3.2 Results

The spatially averaged RMS (root mean square) acceleration was obtained by taking the arithmetic average of the RMS acceleration measured at the 12 evenly distributed measuring locations. Figure 3 shows the spatially averaged RMS acceleration as a function of frequency of the plate with and without the APD pod installed. The peaks in the acceleration in Figure 3 show that the plate has several resonances near 110 Hz, 180 Hz, 200 Hz, 320 Hz, 355 Hz, 400 Hz, and 500 Hz. When the APD pod is installed on the plate the magnitude of several of these resonant peaks is significantly reduced, with some being completely diminished. In particular, it shows that the installation of the APD pod reduces vibrations of the steel plate over a wide range or frequencies, from approximately 100 Hz to 600 Hz.

Note, that for some cases, e.g. the resonance near 180 Hz, it seems that the magnitude of the spatially averaged acceleration of the plate with the APD pod installed is higher than that of the plate without the APD pod. This is a consequence of the frequency resolution of 2 Hz resulting in a cut peak.

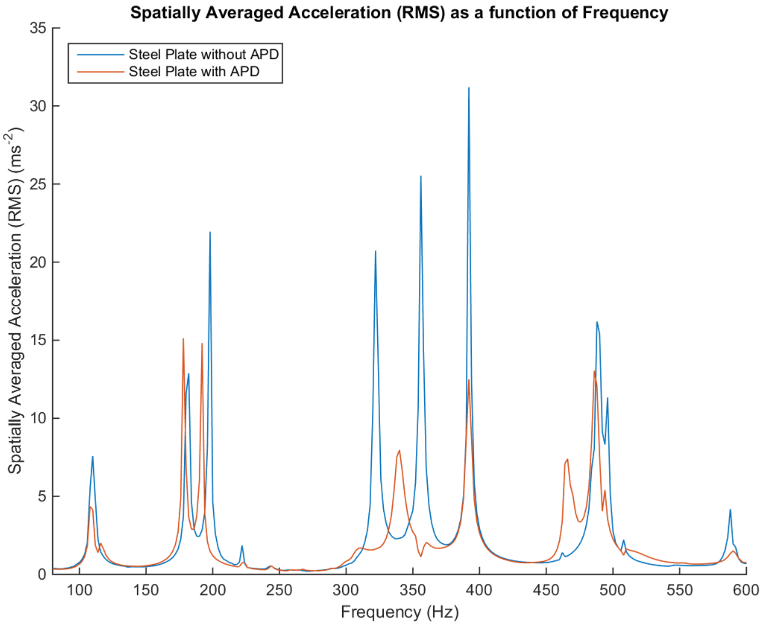

Figure 3 – Spatially averaged RMS acceleration as a function of frequency of the plate without and with the APD pod installed as shown in Figure 2. The installation of the APD pod reduces vibrations of the steel plate over a wide range or frequencies, from approximately 100 Hz to 600 Hz.

4. MODELLING

In this section it shall be described how finite element (FE) models of wind turbines were developed that can predict the effectiveness of the damping of the vibration of the tower through the installation of APD pods. Due to a scaling problem that naturally occurs when modelling APD pods on the tower of a turbine, first simplified models of the native state (i.e. without any mitigation of APD pods) and of the mitigated state are constructed, before complete wind turbine models of the native state and the mitigated state are developed. The full wind turbine models are then used to determine the acceleration of the tower walls and, hence, the sound pressure level (SPL) at a distance of tip height away from the turbine in accordance with standard noise measurements (3).

4.1 Simplified Model

As the height of the APD pods is approximately 10 cm, but the height of the tower is several multiples of 10 m, a scaling problem occurs when constructing a FE model of APD pods placed on the tower of the turbine. One way of overcoming this scaling problem is to simplify the geometry of the APD pods from a 3D object to a 2D shell object with a prescribed thickness.

In order to ensure that the simplified APD pods are representative of the structural behavior simplified models based on the experiments described in section 3.1 were developed in COMSOL Multiphysics. In these models the plate was modeled as a shell object which was excited by a point source representing the shaker. Furthermore, in some models an APD pod modelled as a rectangular shell object was placed in the center of the plate. Figure 4 shows the geometry of the simplified model of the plate with the APD pod.

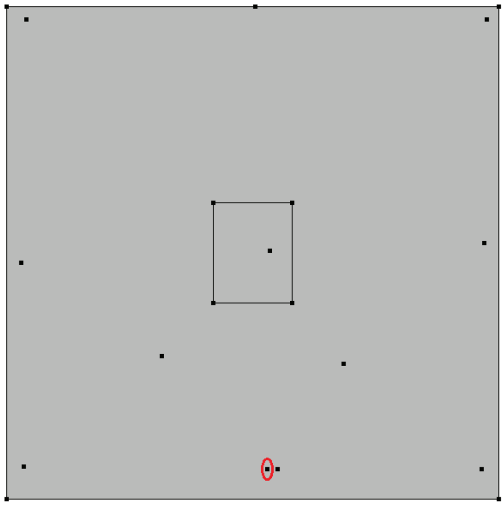

Figure 4 – Geometry of the simplified model, where the rectangle describes the APD pod placed on the metal sheet and the point with the red circle represents the shaker as a point source, as in the experiment described in section 3.1. All other points represent sensors as placed in the experiments.

The models were used to determine the ratio of the spatially averaged RMS acceleration (averaged over the 12 sensor positions) of the steel plate with the APD pod over the native steel plate without the APD pod. This ratio was then used to optimize parameters describing the structural behavior, namely damping ratio and Young's Modulus, by comparing the predicted results of the model with experimental results using a phenomenological approach.

The predicted spatially averaged RMS acceleration of the steel plate with and without the APD pod are given in Figure 5. The peak accelerations predicted by the model are in a comparable frequency range to the peak acceleration observed in the experiments as shown in Figure 3. Therefore, the structural parameter values chosen in this simplified model can be considered to give a representative result for the behavior seen in experiments.

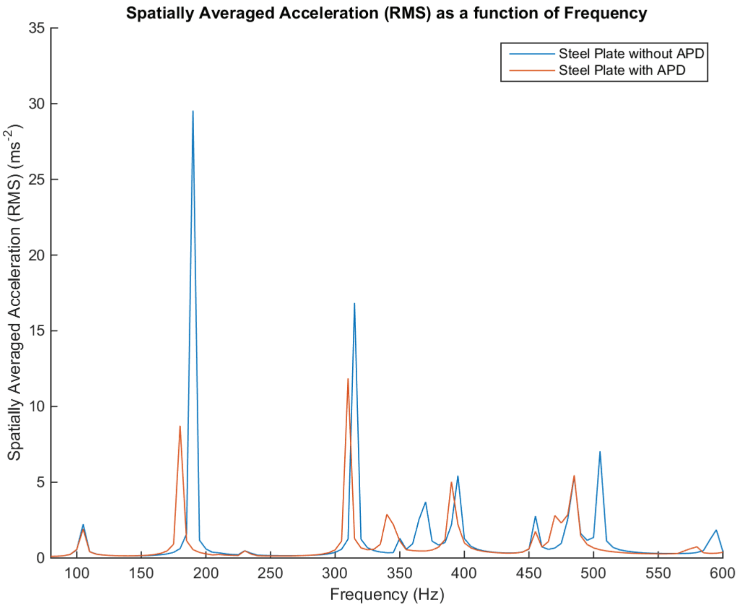

Figure 5 – Comparison of the spatially averaged RMS acceleration of the plate with the APD and the spatially averaged RMS acceleration of the plate without the APD pod for the modelled data.

4.2 Full Wind Turbine Model With and Without APD Pods

FE methods are used to optimize the design and layout of APD pods for reducing tonality of wind turbines. Typically turbine models produced by the authors are validated using vibration measurements of the drive train and tower using accelerometers, blades using laser vibrometry and far-field acoustic measurements. Due to commercial confidentially these data cannot be presented here.

However, to demonstrate the modelling methodology, a generic megawatt scale, variable speed wind turbine has been constructed and is presented. The tower of wind turbine was modelled as a 40 m high shell object, a nacelle with drive train as a combination of shell and solid 3D elements and 3 blades with a rotor diameter of 29.5 m as beam elements. The bottom section of the tower was assumed to have a thickness of 14 mm, while the lower middle section, upper middle section, top section of the tower and the section just below the yaw were assumed to have thicknesses of 12 mm, 10 mm, 8 mm and 13 mm, respectively. The turbine has a three stage gearbox where the tonal noise is caused by gear meshing in the high speed step-up stage. Gear meshing and the related tone vary with rotation speed and are a frequency of 500 Hz when the turbine is operating at its maximum rotation speed. The model is therefore excited by applying an appropriate harmonic load at the surfaces where the high speed stage gear teeth mesh.

In a second model the above described native wind turbine model was modified to include 456 APD pods, which were also modelled as rectangular shells. These APD pods were installed in 76 rings with 6 APD pods each along the complete tower section. The structural parameters for these were chosen as determined in section 4.1. Figure 6 shows the geometry of the second model with the APD pods marked in blue.

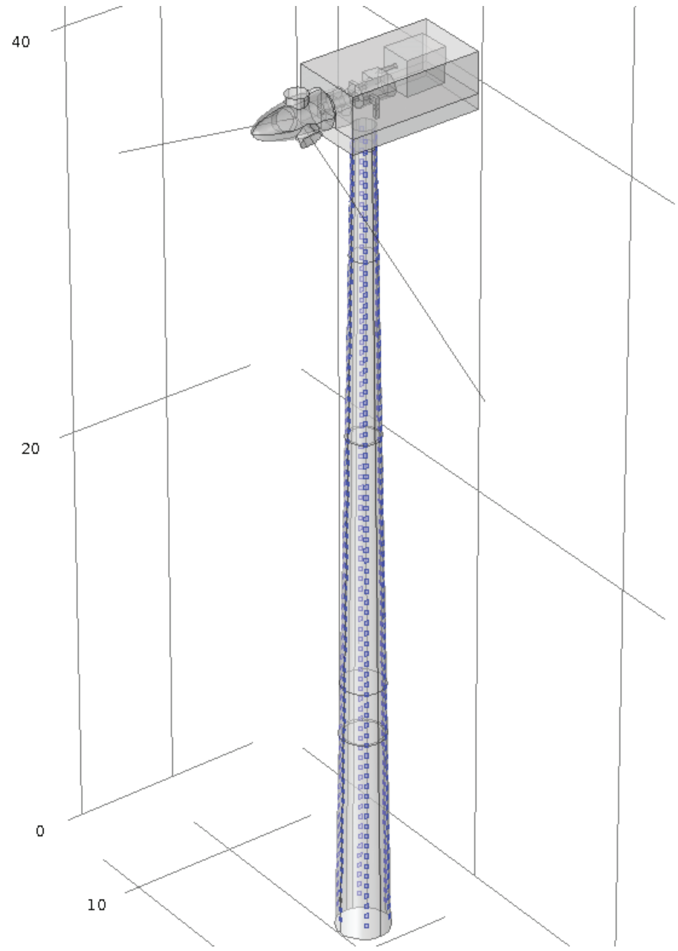

Figure 6 – Zoomed geometry of the wind turbine with APD pods installed. The APD pods are marked in blue.

To determine the surface averaged normal acceleration, the frequency response of the tower to the applied force was computed for the native and mitigated turbine models in COMSOL Multiphysics. The normal acceleration of the tower in both structural models was then used in an acoustic FE model to determine the SPL at 4 different locations, namely downwind, 30° off downwind, 60° off downwind and crosswind, at a distance equal to the tip height of the turbine. In order to determine the effect of the APD pods on the SPL independent of direction, the energy mean over all locations was determined.

4.3 Results of Full Wind Turbine Model

Figure 7 shows the effect of placing APD pods on the tower section on the surface averaged normal acceleration of the complete tower. In particular, it shows that over the whole frequency range from 250 Hz to 550 Hz by placing the APD pods on the tower the acceleration of the tower wall is significantly reduced, especially the peaks near 310 Hz and in the range 340-440 Hz. However, by placing APD pods on the tower the resonances of the tower shift, so that for some frequencies, e.g. ~320 Hz, the acceleration of the tower is actually higher for the tower with the APD pods than the native tower.

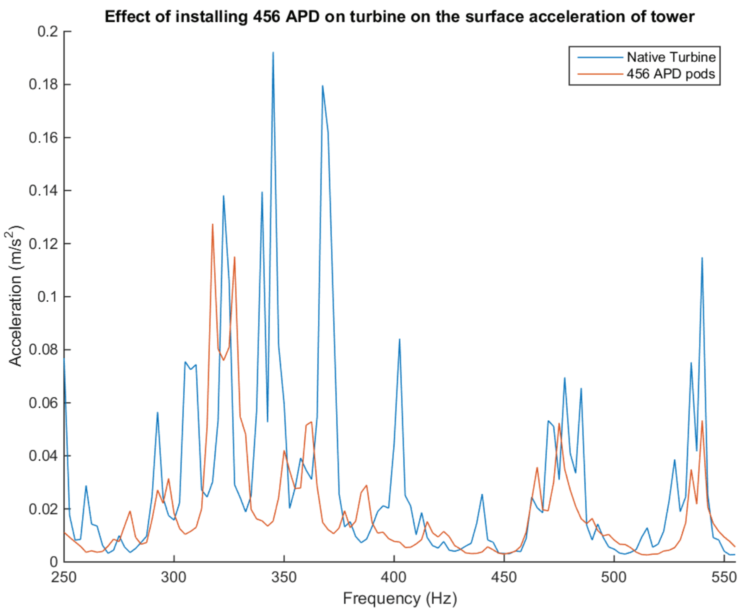

Figure 7 – Surface averaged normal acceleration of complete tower for the native turbine and for the turbine with 456 APD pods installed for frequencies between 250-550 Hz.

Similar observations can be made for the energy mean of the SPL, which is shown in Figure 8. For frequencies between 340-450 Hz the peaks in the SPL are greatly reduced. But as the frequencies of the peaks in the resonances shift due the installation of the APD pods, for some frequencies the SPL is actually higher when the APD pods are installed. Manipulation of these shifts will be explored in the discussion section.

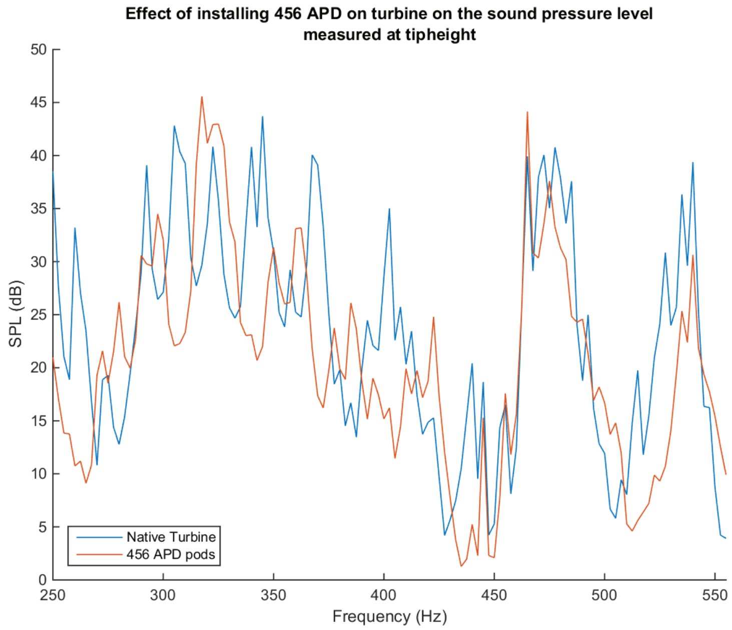

Figure 8 – Energy mean of the sound pressure level (SPL) in dB rel. 20 μPa modelled downwind, 30° off downwind, 60° off downwind and crosswind, at a distance equal to the tip height of the turbine for frequencies in the range 250-550 Hz.

5. DISCUSSION

5.1 Assumptions and limitations of the present models

While the present models indicate that placing APD pods on the tower can reduce tones propagating from the tower significantly over a broad range of frequencies, there are several assumptions used in the model that need to be addressed.

In the present FE models a generic turbine was modelled, which means, in particular, that no experimental data are available to calibrate and compare the modelled normal acceleration of the tower and the SPL.

Furthermore, in the present models only the noise contribution from the tower, but not the nacelle and the blades are taken into account. Background noise is also neglected in the present models.

As mentioned previously, while structural parameters are chosen such that the simplified model of the APD pods is representative of the experimentally observed behavior, the simplified model is not capable of representing the physical behavior of the APD pods, e.g. the APD pods acting as cantilevers.

The APD pods were also placed in a regular pattern on the tower wall. This may not be realistic as structural features inside the tower, such as ladders or flanges, may not allow for a regular pattern.

5.2 Optimization of layout of the APD pod pattern

In the present models 456 APD pods were chosen as their active mass constitutes 5% of the mass of the tower. Furthermore, the APD pods were placed in a regular pattern consisting of 76 rings with 6 equally spaced APD pods in each ring. APD pods are most effective when being placed on sections with the largest displacement (see section 2.2). Thus when targeting a tone or a number of tones knowing the modal shapes of the native tower for these frequencies can optimize the number and position of APD pods necessary to achieve, e.g. a required dB reduction at a receptor location. As seen in Figures 7 and 8 for frequencies near 320 Hz the presently modelled installation of APD pods increase the normal surface acceleration of the tower and SPL, respectively, so that the present configuration could be optimized to avoid this increase.

6. SUMMARY

In this paper APD (Advanced Particle Damping) pods were tested as an alternative mitigation solution for tonal noise which can be particularly annoying to residential communities and which are subject to strong regulatory penalties.

APD pods are metal pods filled with custom granulated elastomers and are effective at damping vibration over a broad range of frequencies as they absorb vibration energy of structural modes at low frequency and dissipate energy of the modes due to the interaction of elastomers at higher frequencies. It was shown experimentally that they can reduce the vibration of steel plates considerably over a broad range of frequencies.

Furthermore, the experimental results were used to inform FE models using a phenomenological approach that can be used to predict the effect of placing APD pods on the walls of the tower of a wind turbine. These FE models were used to determine the vibration of the tower walls and consequently the sound pressure level at several locations.

The placement of APD pods on the tower of a wind turbine increases its damping characteristics leading to significant reductions in the vibration and the tonal noise emissions. By optimizing the APD pod layout on the wall of the tower the largest tonal dB reductions can be achieved, thus benefitting both the local residential communities and the wind turbine owners and operators.

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