Investigation of Soil-Structure Interaction Effects on Damage Detection of Wind Turbine Tower with Biorthogonal Wavelets

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ABSTRACT

The wind has been one of the cleanest sources of energy. The tendency to use wind turbines has been a growing trend in the world in recent decades. The size and capacity of wind turbines are increasing rapidly in order to obtain more wind energy. Statistics show that more giant turbines are more broken down and require more maintenance. Wind farm owners' goal is to monitor work to reduce downtime and increase the efficiency of each wind turbine. The wind turbine tower carries the entire wind turbine and is the second-largest cost of the wind turbine. Damage to the tower can endanger the entire wind turbine and cause extensive damage. However, the background to the study of the wind turbine tower's health monitoring against its mechanical installations is insignificant. Besides, no comprehensive research has been conducted on the tower's health monitoring with soil-structure interaction included. In this study, biorthogonal wavelets were used to process the mode shape of the damaged tower. The foundation is a square concrete foundation 20 m × 20 m and 1 m in depth. Two different soils, a normally consolidated clay and dense sand, are considered. Eighteen failure scenarios were defined. This study indicates that the use of side-to-side mode shapes of the tower has a tangible advantage over its fore-aft mode shapes for detecting the failure. Considering the desirable effect of soil-structure interaction on damage detection, it is necessary to examine this analysis's effect.

KEYWORDS

Wind turbine tower, damage detection, soil-structure interaction, multilevel 2D wavelet decomposition, biorthogonal wavelets.

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Introduction

The wind has been one of the cleanest sources of energy. The tendency to use wind turbines has been a growing trend in the world in recent decades. Wind experts predict the evolutionary and revolutionary growth of wind turbines on land and offshore will continue. On the other hand, statistics show that giant turbines break down more and require more maintenance. At present, the number of wind turbine failures worldwide is about one per day [1]. However, these statistics are similar to an iceberg, only 9% of which is found above the water's surface [2].

The wind turbine tower carries the entire wind turbine and is the second-largest cost of the land-based wind turbine [3]. Damage to the tower can endanger the entire wind turbine and cause extensive damage. However, the background to the study of the wind turbine tower's health monitoring against its mechanical installations is insignificant. Besides, no comprehensive research that has included the towers' health monitoring with soil-structure interaction (SSI) has been conducted. Gross et al. [4] detected wind turbine failure using modal response data. Wind turbine simulation data were obtained by applying the modal hammer test results.

Furthermore, Nguyen et al. [5] used vibration-based artificial neural networks (ANNs) to assess the damage numerically in a real wind turbine tower. However, other studies have been conducted to detect the early failure of wind turbine blades [6-9]. Murtagh et al. [10] showed that considering the flexible soil-foundation system reduces the wind turbine's fundamental natural frequency and increases the damping of the system. In another study, Adhikari and Bhattacharya [11] investigated wind turbines' dynamic behavior on flexible foundations exposed to wind and wave loads. Research by Fitzgerald and Basu [12] emphasized the importance of considering how the soil-structure interacts with the structural control of wind turbines.

In this study, biorthogonal wavelets were used to process the mode shape of the wind turbine's damaged tower. The foundation is a shallow, square, concrete foundation, and two different soils, a normally consolidated clay and dense sand, are considered. Eighteen failure scenarios were defined. Tower damage detection was performed using multilevel 2D wavelet decomposition and decomposition levels 1 to 3.

Methodology

Abaqus/CAE 6.14-2 finite element software was used to model the wind turbine. Figure 1 shows a view of the model. The NREL 5-MW reference turbine specifications have been considered and validated by the results reported by Jonkman et al. [13]. A shallow, concrete foundation and two different soils (a normally consolidated clay and dense sand) were considered in this study, just as they were in Fitzgerald and Basu's study [12]. The Young's modulus of concrete is 30×10^6 kN/m^2; the unit weight is 24 kN/m^3, and the Poisson's ratio is 0.15. The dimensions of the square soil model are 100×100×50 m. Eighteen damage scenarios were defined at the height of 10 m of the tower, including a position at the front of the wind and one lateral to the wind positions. Nine severities of damage were considered based on Young's modulus of steel for the tower. MATLAB R2016b software was employed for signal processing. The two biorthogonal wavelet families of this software, BiorSplines and ReverseBior, were used. Mode shapes of the wind turbine tower were extracted as an input signal using Abaqus/CAE. Then, through multilevel 2D wavelet decomposition, the signal was processed with biorthogonal wavelets at the 1 to 3 levels.

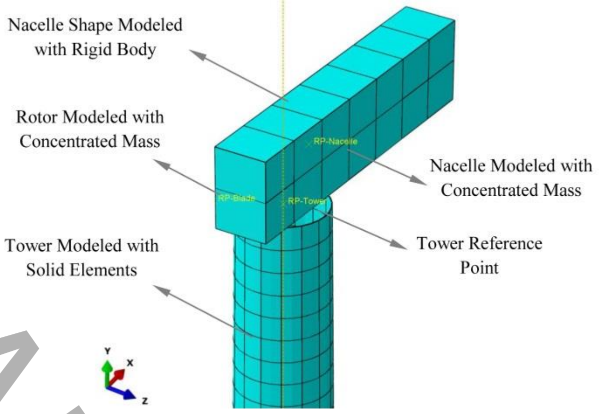

Figure 1. A view of finite element mesh, including the tower and nacelle

Results and Discussion

The mode shapes and natural frequencies of the model were obtained to understand the wind turbine's dynamic behavior. The results of the natural frequencies of this model indicate acceptable accuracy over the natural frequencies of the NREL 5-MW baseline onshore wind turbine. Several analyses were performed to evaluate the effect of SSI on the quality of tower damage detection. For example, Figure 2 shows the number of allowed range answers for damage scenarios 1-9. According to this figure, the soil's effect is significant as we see an increase in the number of allowed range answers by considering the SSI. For damage scenarios 10-18, the soil type only affects the number of allowed range answers from the third mode shapes. This reduced the average number of allowed range answers for soil 2 by 15% compared to soil 1.

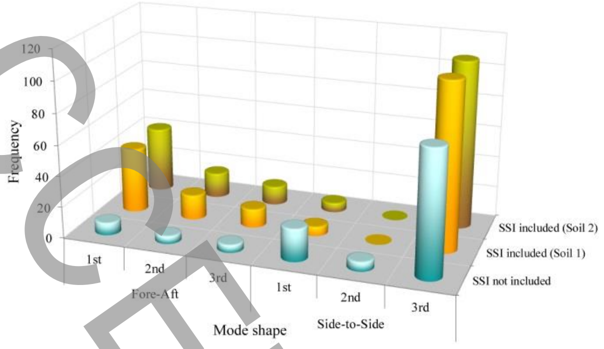

Figure 2. Diagram of the number of allowed range answers for damage scenarios 1-9

Conclusions

In this paper, an extensive analysis of about 30,000 cases was performed to determine the best biorthogonal wavelet for the wind turbine tower's damage detection, and valuable results were obtained. Considering the SSI, the optimal number of damage detection has increased, but the soil type has not been effective for the front of the wind damage scenarios. Nevertheless, for lateral to wind damage scenarios, the normally consolidated clay model's damage is better recognized. Extensive damage detection of the wind turbine model with BiorSplines and ReverseBior family wavelets showed that the ReverseBior family wavelets have a little advantage over the BiorSplines family. According to this study's results, BiorSplines1.1 and ReverseBior1.1 wavelets are suitable for damage detection in wind turbine towers mounted on normally consolidated clay. In this case, the third tower's side-to-side mode shape is used for wavelet decomposition, which should be at the second level. ReverseBior3.3 wavelet is suitable for damage detection in wind turbine towers mounted on dense sand. In this state, the third tower's side-to-side mode shape is utilized for wavelet decomposition, which should be at the first level.

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