Chapter 5
Preliminary Investigation of an Operating Wind Turbine in a Seismic-prone Area

Mona Amer, Tomás Núñez, and Carlos E. Ventura

Abstract Areas with high wind resources for wind turbines often coincide with earthquake risk areas. To enlarge the application of wind turbines in these regions, it is thus, necessary to study and understand the dynamic behavior of operating wind turbines in seismic areas. Currently, there is a lack of experimental studies on these types of structures under seismic conditions. The proposed research shall change the state of the art by performing a long-term field study on wind turbines located in high-risk earthquake regions. In a period of at least one year, data will be continuously captured. In a high-risk earthquake country, such as Chile, an earthquake with a magnitude of six or higher occurs in almost every year. The data will be used to draw conclusions on the dynamic behavior of wind turbines under seismically induced loads and to derive suitable structural health monitoring techniques. For a preliminary analysis, data from a 20-hour-measurement of a wind turbine in Chile is used. Challenges associated with the data analysis are identified and discussed to prepare the following long-term field study. These insights of the proposed study will enhance the development of structural health monitoring serving as part of digital twins for wind turbines.

Keywords Wind energy · Earthquake Engineering · Structural Health Monitoring · Operational Modal Analysis · Digital Twin

Introduction

The transition to renewable energy is one of the key challenges faced by our current society. Wind energy represents one of the main pillars for reaching the energy transition. Areas with high wind resources often coincide with regions that have a high seismic activity [1]. For this reason, it is important to study and comprehend the structural behavior of wind turbines in these areas and under seismically induced loads to adjust the design guidelines and develop suitable structural health monitoring techniques.

Currently, the structural design of wind turbines is not standardized within the building code and design guidelines only rely on simulations in the case of earthquakes [2]. For this reason, there is no consistent procedure on how to perform structural analysis and mitigate structural failure in the design process. Simulations are subjected to simplifications some of which are not tenable in case of earthquakes. Under earthquake loads usually negligible effects gain more importance [2], such as the influence of higher modes, since the vertical modes (usually associated with higher natural frequencies) are excited during an earthquake [3]. This, in turn, can have an impact on maximum deflections at the top of the tower, which can also affect rotating components in the nacelle and can lead to potential damage. The only published experimental study has been performed by Prowell et al. [4] on a scaled wind turbine that has been excited by an outside shake table. A long-term field study actually capturing the load of earthquakes acting on the wind turbine structure is necessary to generate important validation data. This applies especially to specific parameters such as the damping behavior, which is usually determined experimentally. The experimental validation data will provide consistent guidelines for the structural design and assessment of wind turbines in seismic areas. Therefore, such a study is proposed and described in detail below.

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Methodology

For the realization of the proposed study, an earthquake-intensive country such as Chile is chosen, where almost every year an earthquake with a magnitude greater than six is recorded, causing damage to buildings and other structures. Up to four wind turbines will permanently be instrumented with acceleration sensors, which will transmit the acquired data to a remote server, to which researchers have access. For the measurement, senors of type ADXL 355 can be applied, which have proven successful in previous structural health monitoring approaches and represent a cost-effective solution at the same time [5]. Data is recorded over a long period until a significant earthquake event can be recognized. After the earthquake event, another field trip will be scheduled to assess the structural health of the wind turbine that has been seismically excited. This knowledge and experimental data set will help understand, what effects play a major role during an earthquake and what measures have to be taken by potential structural health monitoring approaches to avoid structural damage.

Since there is no data from a real wind turbine under seismic excitation available yet, data from a 20-hour-measurement of a wind turbine in the South of Chile close to Los Ángeles is used for preliminary investigations. The turbine is rotating during measurements. Understanding the dynamic behavior of a wind turbine under similar conditions as the ones studied at a later point in time, will help to set up a suitable test plan and to identify the challenges associated with the data analysis.

The modal identification of modal parameters in operation is the core objective of the data analysis. Modal parameters can be tracked over time. An observed shift in these parameters can be evidence of structural changes and allows for early on maintenance before any damage occurs [6]. This knowledge can thus be used to design structural health monitoring approaches. The development of a dynamic model by means of modal parameters is the focal point of the ongoing evaluation.

The structural information is sampled with a frequency of 128 Hz by means of four velocity sensors, which are placed inside the tower. Two sensors are opposite to each other on top of the tower, just below the nacelle, and the other two sensors are distributed along the height of the tower.

It is important to mention that the rotational speed signal is sampled at $f_s = 0.0017$ Hz, which means that there is one time stamp every 10 minutes capturing this dimension. The rotational speed is depicted as a function of time during the whole measurement in Fig. 1. For the analysis, time sections are chosen, where the speed remains constant for at least two consecutive time stamps. Three time ranges with an average constant rotational speed of 6 rpm, 9 rpm, and 10.5 rpm are chosen for the preliminary analysis. These sections are marked in Fig. 1 with red color. Nevertheless, speed fluctuations within the selected data sets can occur the extent of which remains unknown.

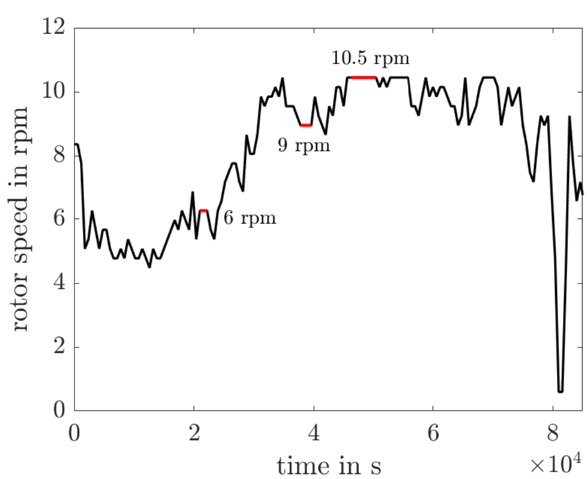


Fig. 1 Rotational speed as a function of time during the ambient vibration tests.

Results

In the following section, the challenges arising from modal identification are discussed. The modal identification from ambient vibration tests of a structure with rotating components is always associated with the problem of superimposing harmonic response parts that hinder the reliable identification of structural parameters.

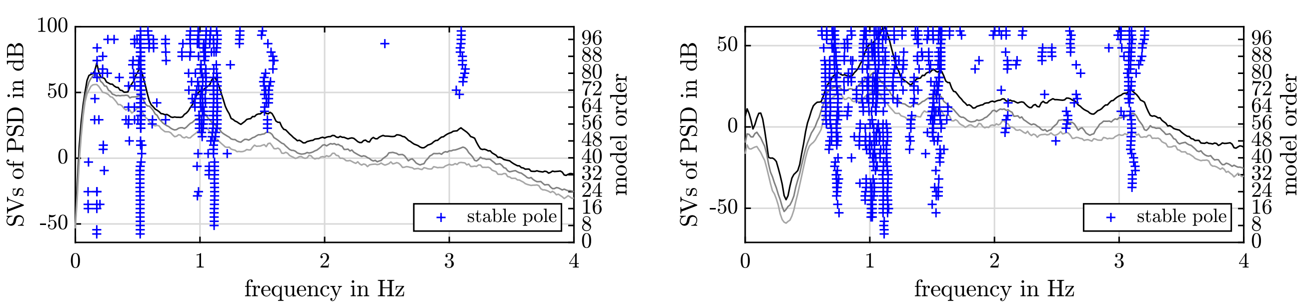
From standstill conditions, it is known that the lowest natural frequencies are expected around 0.14 Hz. The next natural frequencies are at 0.56 Hz, 0.67 Hz, 1.1 Hz, 1.16 Hz, and 1.54 Hz. Subsequently, the data of the highest rotational speed at 10.5 rpm will be discussed in more detail. The first rotor harmonic is at approximately 0.175 Hz. Due to the number of blades, the third harmonic is also significant in the measured response data. Beyond this, the influence of the sixth harmonic can be observed. It is evident that the frequencies of the harmonics are very close to some of the structural frequencies or even overlap with them completely. A strong influence of the rotation in the data is expected.

In [7], a technique was proposed to eliminate the harmonic response from the measured response and obtain the purely stochastic part of the vibration response. This, in turn, can be used as input to established algorithms for operational modal analysis. For the technique, a rotary encoder signal is used, which provides the phase information of the rotor at every measured time instant. This allows for a minimally-invasive procedure with respect to the measured structural response and can additionally account for rotor speed fluctuations.

Since the rotary encoder signal is not available, the approach for the elimination of the harmonic signal content presented in [7] cannot be applied. A phase signal of the rotor synchronized with the actual structural response measurement would have been necessary. Instead, the approach described in [8] is applied to the data. The rotational speed is estimated as one constant value over the measurement period.

In Fig. 2, the stability diagram resulting from the modal analysis is illustrated over the first three singular values (SVs) of the resulting power spectral density (PSD) before and after the elimination of the harmonic response. In this case, the elimination leads to a strong effect on the neighboring frequency area that results in the accumulation of calculated poles in the area next to the frequency range influenced by the elimination. Adjusting the different parameters used within this techniques could lead to an improved result. The preliminary analysis shows the dominance of the harmonic effect, which is superimposing the structural natural frequencies of the system that cannot be identified reliably. The result also shows that within the whole measurement period of 80 minutes, strong rotor speed fluctuations occur, leading to the wide peak of the harmonic in the frequency domain and the strong influence when eliminating the harmonic response part. The preliminary analysis shows that there is a need for application-specific techniques to deal with the harmonic effect in the data. Testing different techniques and developing suitable methods to handle the harmonic influence is part of future research.

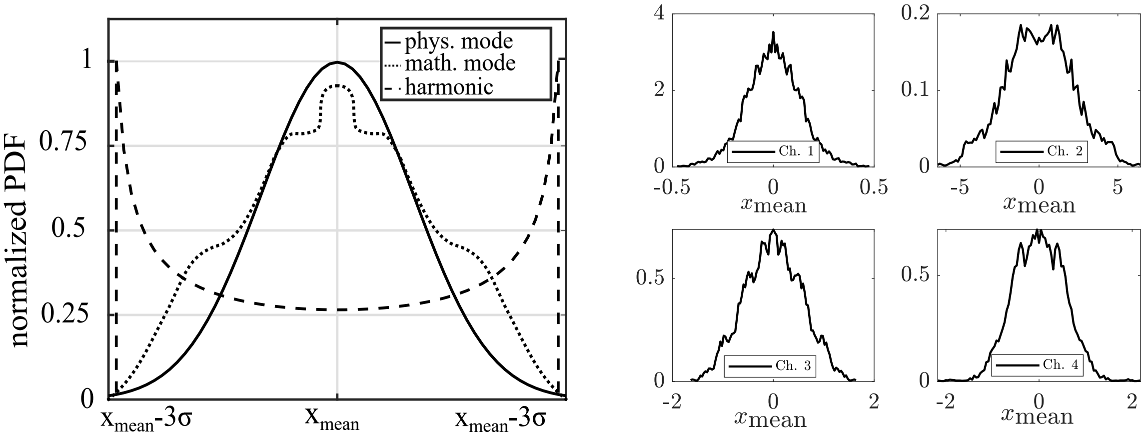
Another approach to identify harmonics, is the use of the probability density function (PDF). According to the shape of the PDF belonging to the mode investigated, a user can classify this mode as a structural mode, a harmonic, or even a mathematical pole that has been calculated, but does not represent any physical behavior, compare Fig. 3a. An example, for the third calculated mode in operation at around 1 Hz is depicted in Fig. 3b. From Fig. 3 it can be concluded that the interpretation of the PDF is complicated, since the PDF does not show a clear shape, which does belong to one of the defined possibilities. The PDF depicted in Fig. 3b rather describes a mixture of the possible scenarios. This underlines, once more, the complexity of the available data set from the rotating wind turbine and the necessity for specific tools to reliably identify the modal parameters.



(a) before harmonic elimination

(b) after harmonic elimination

Fig. 2 Stability diagram displaying the first three singular values of the measured structural response's PSD before and after the elimination of the first harmonic.



(a) Example of PDFs (b) PDF of calculated mode

Fig. 3 Probability density function (a) depicted as examples for the different types of modes, (b) of each measurement channel for a calculated mode at approx. 1 Hz.

Conclusions

For a better understanding of the dynamic behavior of wind turbines in earthquake regions, a long-term field study, instrumenting several wind turbines in high-risk seismic areas, is intended. To study the characteristics, of wind turbines in such kind of areas, a 20-hours measurement from a wind turbine operated in the South of Chile served as a basis for a preliminary analysis. From this analysis, it can be concluded that the influence of the rotation is predominant and suitable measures have to be found and applied to the data to enable the reliable modal identification. The only way for a successful data analysis, is the elimination of the harmonic response part, since the harmonic frequencies are too close to the natural frequencies of the system. An estimation of the harmonic response using a Kalman filter approach in combination with the row space projection of the raw data onto the orthogonal complement of the row space of the estimated periodic part as proposed in [9] could serve as a way to deal with the strong harmonic influence. Based on these future results, further conclusions can be drawn and necessary adjustments can be made to find a suitable technique to treat the harmonics and be able to reliably identify the modal parameters in operation. Having identified a modal model under varying load conditions, especially during ground motion excitation, will enable the development of structural health monitoring approaches that can serve as part of digital twins for wind turbines in seismic areas.

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