Wind Turbine Monitoring Using Optical Motion Magnification: Challenges and Opportunities

TYMON B. NIEDUZAK, NITIN N. KULKARNI, CHRISTOPHER NIEZRECKI and ALESSANDRO SABATO

ABSTRACT

An inexpensive, quick, and robust structural health monitoring technique to assess the integrity of wind turbine foundations and components remains elusive. Traditional techniques for wind turbine condition monitoring (CM) are costly, invasive, and cause downtime in the asset. As turbines age, wear-induced damage may accumulate in the structural and mechanical components. The ability to effectively monitor wind turbine foundations and blades using optical methods is explored in this work. Specifically, optical motion magnification (OMM) is investigated for this application. OMM is a computer vision-based monitoring technique that can extract and amplify unperceivable displacements in a video of a structure of interest. These magnified videos effectively reveal the areas in a system with the largest displacements. OMM is a remarkable visualization tool, giving technicians the ability to quickly identify areas with problematic vibrations in an easily understood manner. OMM also generates quantitative displacement time histories from which the amplitude and frequency spectra of the structure can be extracted. This work describes two experimental studies completed to determine the feasibility of OMM when this approach is used to inspect wind turbine foundations and blades. Firstly, an experiment exploring the use of OMM for modal analysis of turbine blades was performed, comparing the frequency spectra calculated using both optical and traditional contact-based measurements. OMM proved capable of identifying resonant frequencies with an error less than 2.5% when compared to conventional measurements. Next, proof-of-concept turbine foundation tests were completed to ascertain the viability of the method to distinguish between questionable and healthy foundations. The results of this research show how OMM can potentially eliminate several issues inherent in standard testing and monitoring procedures, namely reducing the overall cost of the sensor systems and time spent collecting data. If further developed, OMM can open the doors to many more innovative solutions, applications, and optimizations of current CM practices for large-scale engineering systems.

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INTRODUCTION

Wind Turbines (WTs) are large structures that generate electricity from spinning components which are rotated by the wind. These systems are generally composed of an anchoring foundation that supports the dynamic and static loads of the entire structure, a tower that is usually made of steel or concrete, a nacelle that houses the electrical and mechanical elements, and three blades attached to a rotor. The foundation and its interface with the tower are critical components of a WT, and their deterioration will reduce the WT's resilience. Because WTs are growing in size to keep up with increasing energy demand, foundations are now growing bigger too [1]. In addition, because older turbines are often repowered (i.e., by replacing part of the structure with larger and more powerful components that use the latest technology), foundations are exposed to forces bigger than the design specifications, causing increasing stress and strain beyond the limit states of the original structure. WT foundation failures account for only 1.5% of total WT failures and 1.2% of total turbine downtime [2]. Even though foundation failures are not very common, they are very important to study in order to prevent catastrophic failures that can result in the total loss of the entire WT. In addition, WT foundations are very expensive, gravity spread foot shallow foundations making up 17% of the total capital turbine cost [3].

For these reasons, foundation monitoring is critical to ensure proper functioning of the asset. Typically, the condition of a WT foundation is initially assessed by above-ground visual inspections of exposed surfaces [1, 4] or through lengthy and expensive excavation campaigns and coring [5] [6]. If cracks are found, dye testing or endoscope inspections are performed to determine if the fracture is active or passive. All these techniques are destructive and require potentially substantial repairs or retrofitting without assurance that all issues are remedied. Other tests, like the Pull Off test, which evaluates the compressive strength of concrete [7], can be performed on turbine structural materials before installation, but once the system is assembled, these tests are no longer appropriate. In addition, throughout all these procedures, the WT undergoing inspection must be parked and can experience a significant downtime.

As an alternative to these destructive approaches, sensors such as accelerometers, tiltmeters, Linear Variable Differential Transformers, and strain gauges have long been utilized for monitoring the dynamic behavior of WTs [8] [9, 10]. These sensors can be placed at numerous key points of the structure to extract displacements, dynamic behavior, and resonant frequencies of the targeted system and infer the conditions of the foundation. However, contact-based measurement systems only provide information at very few discrete points, which may fail to detect the onset of structural changes representative of damages in the targeted system. In addition, due to the high installation costs (i.e., ~$3,000 per turbine), unpracticality, and the uncertainty in correlating the measured quantities with the real conditions of the WT, widespread Condition Monitoring (CM) is not financially attractive or practical to implement [6]. Currently, a quick, inexpensive, and accurate CM technique to assess the integrity of WT foundations remains elusive and motivates this study.

The purpose of this work is to quantify the feasibility and accuracy of computer-vision techniques for Structural Health Monitoring (SHM) of WT foundations and components. In particular, this study investigates the use of Optical Motion Magnification (OMM) to measure imperceptible motion from a video of a turbine to identify displacements indicative of foundation failures. OMM is a vision-based, non-contact structural monitoring technique, which relies on ordinary video to extract imperceptible structural motion [11-14]. In addition to producing qualitative animations of magnified motion, OMM can be used to extract displacement time histories and frequency spectra to quantitatively assess the condition of the structure [15]. This method can help determine the health status of a structure as well as locate sources of damage or potential failure.

An experiment exploring the use of OMM for the modal analysis of turbine blades was completed as well as proof of concept turbine foundation tests. The blade's resonant frequencies identified by the OMM system corresponded very well with those found using traditional contact-based measurements. The optical turbine foundation measurements also confirmed the efficacy of this technique for WT CM applications as the results aligned with trends confirmed by the wind farm owner-operators.

EXPERIMENTAL SETUP

Laboratory and field tests were performed to validate the accuracy of OMM for WT foundations and blades SHM. These tests included a **i)** back-to-back comparison with accelerometers to extract the resonant frequencies of a utility scale WT blade during a modal test and **ii)** measurement campaign on in-service WTs to monitor the dynamic behavior of the foundations.

The first set of tests was performed to evaluate OMM's ability to extract accurate dynamic characteristics of a targeted system such as resonant frequencies and Operating Deflection Shapes (ODS). A modal test was performed by performing pluck tests on a utility scale WT blade cantilevering from a concrete anchor and recording a video of the trailing edge of the structure (see Figure 1a). In particular, a 5-Megapixel Iris M camera fitted with a 12.5 mm focal length lens was placed at a working distance of 33 m from the blade and setup to collect videos of the vibrating structure for 40 seconds at 200 fps [16]. It should be pointed out that during the test, the camera was not perpendicular to the edge of the WT blade but at an angle ~20°. Two triaxial MEMS accelerometers model 3713B112G manufactured by PCB Piezotronics with a nominal sensitivity of 1000 mV·g^{-1} were used as reference to measure the resonant frequencies of the blade [17]. The accelerometers were set to record at a sample at 200 Hz and attached at the tip of the blade and ~10 m down the blade.

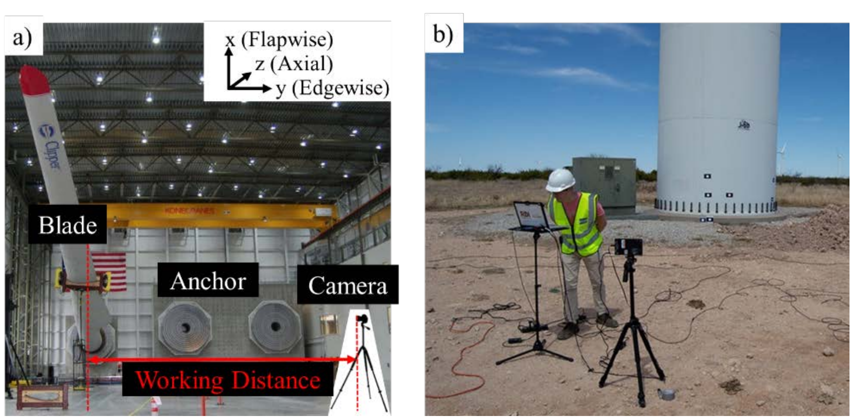

Figure 1. Experimental setups for the two tests performed: a) experimental setup used to extract the flapwise resonant frequencies and ODS of the blade during the modal test and b) Mr. Nieduzak collecting videos of a WT foundation during field tests.

The second set of tests was performed to evaluate the capabilities of OMM in measuring the displacement of WT foundations at an operating wind farm. Videos of several WTs were collected during a two-day testing campaign using the same camera used during the modal tests fitted with 12.5 and 25 mm focal length lenses. The tests were performed by placing the camera on a tripod (see Figure 1b) and collecting 45-second videos with the camera parallel to the direction of the nacelle in order to extract the point of maximum displacement in the rocking foundation. During the tests, a selection of healthy foundations was optically monitored while the WT was operating to determine baseline motion measurements. Similarly, turbines exhibiting abnormally large foundation displacements (i.e., referred to as "*questionable*" for the remainder of this paper) were monitored utilizing the same procedure.

ANALYSIS OF THE RESULTS

In this section, the results of the modal tests and field measurement campaign are summarized. For both datasets, the videos recorded using the Iris M camera were processed using the RDI Technologies' Motion Amplification software to extract the displacement time histories in both the vertical (i.e., Y-axis) and horizontal (i.e., X-axis) directions of different regions of interest (ROIs) on the surface of the targeted structure. Regarding the modal test, Figure 2 plots the frequency spectra obtained from the Fast Fourier Transform (FFT) of the signals collected by the accelerometers and the camera while a numerical comparison showing the relative error between the resonant frequencies obtained by the two methods is summarized in Table I.

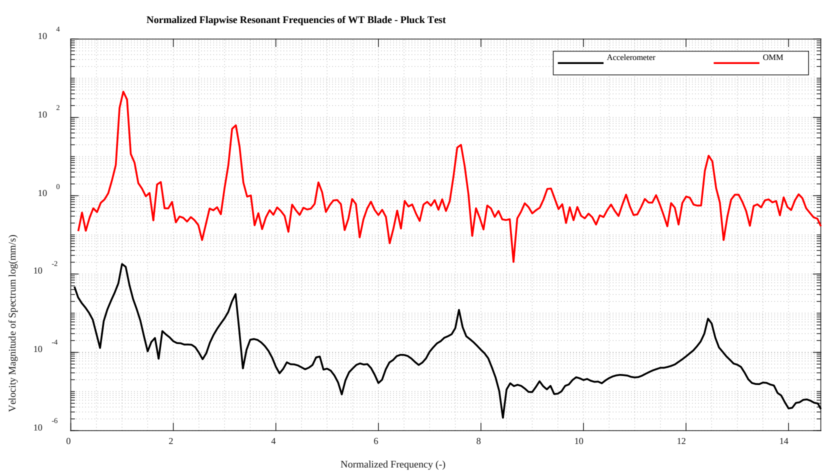

Figure 2. Flapwise frequency spectra calculated from accelerometer and OMM normalized with respect to the first resonant frequency measured by the accelerometer.

TABLE I. COMPARISON OF FLAPWISE RESONANT FREQUENCIES CALCULATED FROM ACCELEROMETER AND OMM DATA.

Accelerometer (-)	1.00	3.21	7.57	12.43
OMM (-)	1.02	3.22	7.61	12.44
Difference (%)	2.46	0.18	0.48	0.09

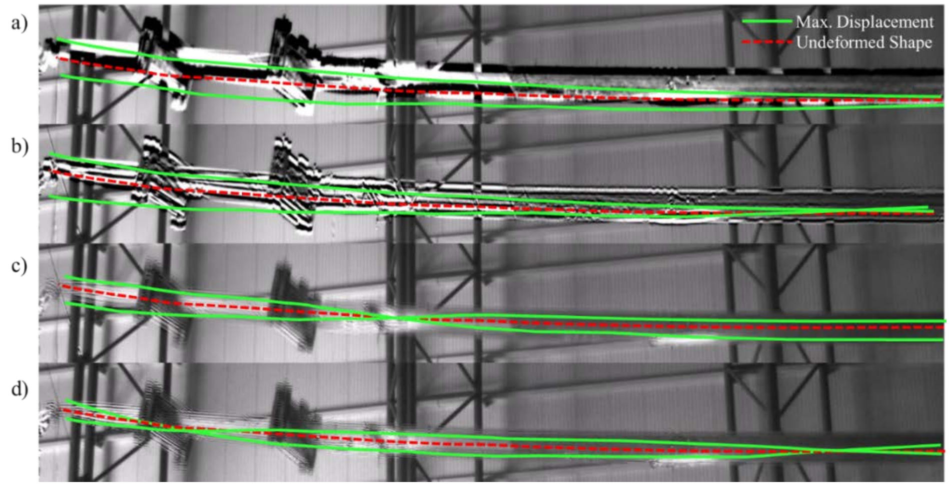

Figure 3. Screen capture of the OMM video showing the points of maximum displacement for the first flapwise ODS of the tested WT blade: a) 1st bending ODS; b) 2nd bending ODS; c) 3rd bending ODS; d) 4th bending ODS.

It should be noted that in both Figure 2 and Table I, all the frequencies have been normalized to the value of the first resonant frequency of the blade measured by the accelerometers. Also, the accelerometer data were integrated to obtain velocity in order to compare with the spectrum produced by the OMM software. As observed from Figure 2, all the frequency peaks of both measurements correlate well in terms of resonant frequencies and the two methods identify resonant frequencies with a maximum relative error below 2.5%. The optically determined frequency spectrum corresponds well with the reference accelerometer measurements and the first four Flapwise bending resonant frequencies of the WT blade are accurately identified. However, because the FFT were generated using output-only measurements and because the camera had a 20° angle with respect to a plane vertical to the surface of the blade, the amplitudes of the signals are not directly comparable. When the four frequency peaks are individually isolated with a Band Pass Filter (BPF) of ±0.1 Hz around the frequency of interest and processed using OMM, the ODS of the blade can be visualized. Figure 3 shows the frame of maximum displacement extracted from the OMM-filtered videos where the nodes of the different ODS considered are clearly visible.

Concerning the field tests, a Low-Pass Filter (LPF) from 0-3 Hz was applied to the videos prior to processing with OMM to remove any high frequency information that may be corrupting the foundation measurement. Data was then analyzed in terms of the RMS values of the displacement time waveforms to generate a comparable metric between healthy and questionable turbines. Figure 4 and Figure 5 show the results of the X and Y displacements extracted from two ROIs in correspondence of the WT foundation and tower for two distinct structures. In particular, Figure 4 shows the response of a heathy foundation facing 12 $m \cdot s^{-1}$ winds coming from the south with the camera almost parallel to the wind direction and the nacelle. The RMS values of the extracted displacement time histories were equal to 0.06 mm in the X-direction (see Figure 4b) and 0.29 mm in the Y-direction (see Figure 4c).

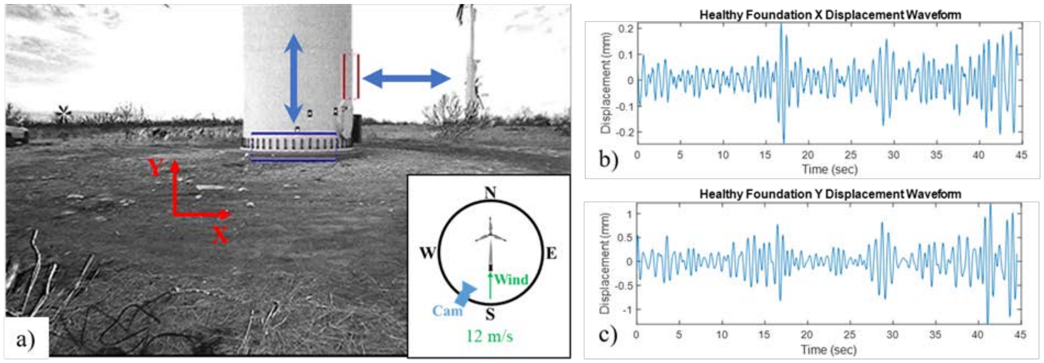

Figure 4. Results of OMM analyses on healthy foundation: (a) frame of magnified video detailing the vertical and horizontal ROIs and experimental context; (b) displacement time history in the X-direction; and c) displacement time history in the Y-direction.

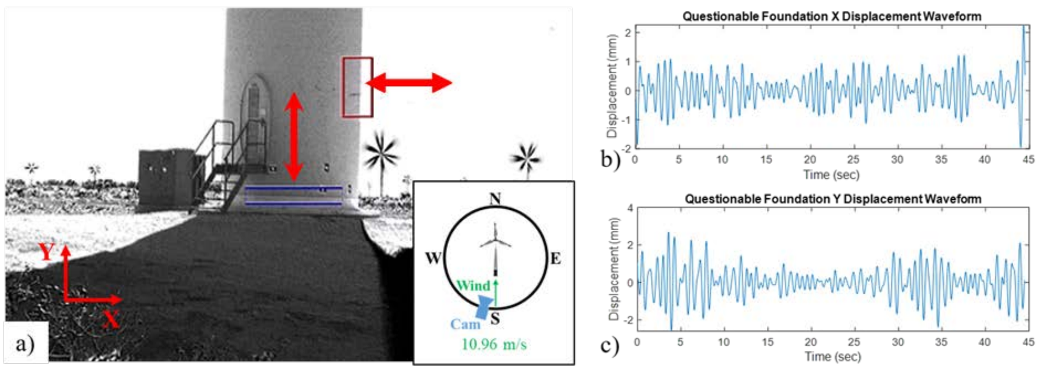

Figure 5. Results of OMM analyses on questionable foundation: (a) frame of magnified video detailing the vertical and horizontal ROIs and experimental context; (b) displacement time history in the X-direction; and c) displacement time history in the Y-direction.

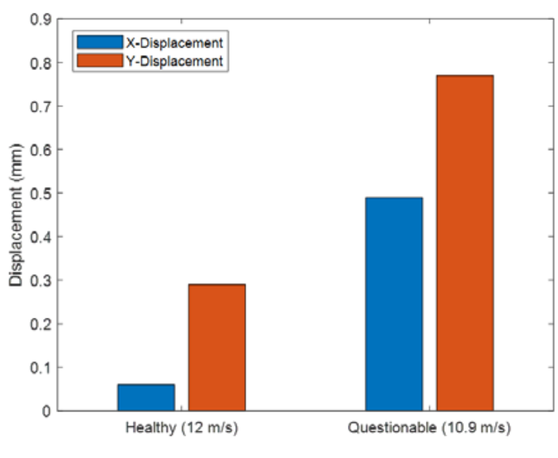

Figure 6. Comparison of vertical and horizontal RMS displacement values measured for the healthy and questionable WT foundations.

A similar procedure was adopted for videos recorded of questionable foundations. Figure 5 shows the response of a 1.62 MW turbine facing 10.96 ms^{-1} winds coming from the south recorded with the camera almost parallel to the wind direction and the nacelle. The RMS values of the displacement time histories extracted from the ROIs highlighted in the video frame shown in Figure 5a were 0.49 mm in the X-direction (see Figure 5b) and 0.77 mm in the vertical Y-direction (see Figure 5c).

By comparing the RMS displacement values in both the horizontal and vertical directions, the questionable foundation is shown to exhibit significantly larger displacements than the healthy foundation even though the wind speed was slightly lower (see Figure 6). This result demonstrates the efficacy of the OMM technique for this application as it can successfully identify some differences in foundation motion between different turbines. Finally, a motion magnified video showing a visual comparison between the displacements of the healthy and questionable foundations can be found here: https://youtu.be/Uz72d4mTbo0.

CONCLUSIONS

In this study, the capabilities of OMM for assessing the condition of WT foundations and blades are investigated. The final goal of this research is to advance a non-contact, automated, inexpensive, and fast method for identifying defects or damages before they become failures in service. The accuracy of the OMM technique was validated by running experiments on utility scale WT blades to extract structural dynamics parameters. Videos of the blade undergoing a modal test were recorded using a 5 Megapixel camera, and OMM was used to extract the first four resonant frequencies of the structure. The extracted frequencies were compared against a reference accelerometer, showing how the proposed OMM method can identify the resonant frequencies of the WT blade with a maximum error below 2.5%. The high correlation between optical and traditional measurements confirms OMM's ability to correctly identify resonant frequencies. The first four flapwise ODS of the blade were then isolated by filtering the collected videos with a BPFs of ±0.1 Hz around the frequency of interest. The consistency between the filtered motion magnified videos and the theoretically expected ODS at the respective frequencies supports the accuracy of this optical technique for modal analysis.

The OMM system was then tested in the field on healthy and questionable WT foundations in operation. A comparison of optical measurements made at similar camera angles and distances demonstrated that OMM has the ability to identify differences in foundation motion between healthy and questionable turbines. The healthy turbine had a vertical displacement RMS of 0.29 mm while the questionable turbine had a vertical displacement RMS of 0.77 mm. While the results shown in this study support the efficacy of the OMM algorithm in differentiating between healthy and questionable turbines, it should be noted that optical data was not compared to synchronous measurements collected with traditional sensors for reference. While additional studies are required to validate the accuracy of the OMM approach, if further developed this technique could reduce time and cost for condition-based maintenance of WT foundations and other components of a wind farm. OMM would represent an easy-to-use, effective, and autonomous SHM system that would allow the detection of potentially dangerous situations while not interfering with operations of the inspected structures.

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant Number 1916715 (Collaborative Research: I/UCRC for Wind Energy, Science, Technology, and Research). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would like to thank the WindSTAR sponsors for the funding of this project and the IAB mentors for their assistance, suggestions, and feedback.

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