Developing Digital Twins of Dynamic Systems Using Vision Techniques, Multi-View Stitching, and Expansion Methods

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ABSTRACT

This study aims to create digital twins of structures such as wind turbines using non-contact techniques integrated with numerical methods. As part of this study, a stereo camera system mounted on a semi-autonomous drone captures the dynamic properties of a wind turbine. The drone with digital image correlation (DIC) cameras scans the entire structure to capture the deformation data of each field of view. The measured data includes the geometry, and displacement field data is mapped into a global coordinate system using 3D transformation matrices. The obtained data in the time domain for each field of view is transformed into the frequency domain to extract the operational deflection shapes and resonant frequencies for each field of view. The obtained deflection shapes are scaled and stitched in the frequency domain to extract the operating deflection shapes of the entire turbine. The operating data for the wind turbine is expanded using modal transformation techniques. A numerical model of the turbine is updated using expanded modal data. This methodology can be applied to any mechanical system subjected to dynamic loads. The work provides engineers with a new procedure to create and update digital twins using a limited set of measured data captured with non-contact techniques. The proposed approach to creating digital twins of structures can be used for full-field structural dynamic predictions, durability analysis, and structural health monitoring.

INTRODUCTION

The increasing use of wind energy as a renewable power source has led to significant growth in the number of wind turbines installed worldwide. However, as wind turbines operate in harsh environments and under varying conditions, they are subject to various mechanical cyclic stresses and potential fatigue failures. Thus, there is an increasing need for inspection techniques for wind turbines.

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Optical techniques are very useful for health monitoring purposes as they can obtain full-field data and do not interfere with the operation of the system. Digital image correlation has recently received special attention in the field of structural dynamics [1, 2] because it can be used to obtain full-field data in a very short acquisition time. This approach has been used for measuring vibrations of wind turbine blades [3-5], helicopter rotors [6-9], bridges [10, 11], human skin [12, 13], and infrastructure [14, 15]. Researchers have also used motion magnification [16, 17] and blind source separation techniques [18] to extract the vibration characteristics of structures. However, a pair of DIC cameras may have a limited line of sight only on a certain part of a large complex structure. This makes it very difficult to use DIC for the vibration measurement of large structures. To resolve this issue, researchers have used multiple pairs of cameras coupled simultaneously to measure the deformation of large structures [19]. The use of multiple pairs of cameras involves excessive cost, which may not be feasible. Patil, Baqersad et al. proposed a new technique to scale the mode shapes using measured force and stitch the mode shapes in the frequency domain [20, 21]. However, it might not always be feasible to obtain a proper understanding of the health of the structure using only operating data.

In this paper, an approach is proposed to develop a digital twin of wind turbines for structural monitoring and inspection. The approach is based on stitching the operating mode shapes of a structure and obtaining the full-field response for a complex structure. The DIC cameras roved over the structure using a drone to obtain the response of the structure in multi-views. Furthermore, the deformations in the time domain obtained using the DIC technique are filtered and transformed into the frequency domain. This frequency domain data is then used to extract the natural frequencies and operating deflection shapes of each section of the structure. Later, the obtained operating mode shapes of each section are scaled and stitched together to obtain the operating mode shapes of the entire structure. This data will be applied to the numerical model of the structure to create a digital twin of the structure for monitoring and inspection.

METHODOLOGY

The objective of this project is to develop a methodology for creating a digital twin of structures experiencing dynamic loads using DIC. The digital twin can be used for failure predictions, durability analysis, and structural health monitoring. The work is conducted in two steps.

In the first step, a multi-view DIC technique is used to measure the dynamics of structures with complex geometries. The technique works based on stitching the views in the frequency domain rather than the currently used approach that stitches the views in the time domain. In this technique, the response of the structure to excitation is measured using a DIC system. The measured response is transferred to the frequency domain to extract the operating shapes of the structure. A similar procedure is repeated for data measured from other views of the structure. It should be noted that there is a common section between every two adjacent views containing at least three points that are later used to stitch the operating mode shapes of different views. The proposed technique uses a uniform scaling factor that facilitates the stitching of the obtained operating shapes by roving the stereo system around the structure.

In the second step, a strain expansion algorithm is developed based on the strain mode shapes of the structure. It is expected to see that the strain mode shapes for the expansion would lead to a very accurate predicted strain. Using this approach, real-time operating data at few strain-gages can be expanded to extract full-field strain data for structural health monitoring and durability analysis.

The multi-view DIC system (Figure 1) is integrated with the strain expansion algorithm (Figure 2) to develop a digital twin of the structure that can be used for structural health monitoring. A drone is used to carry the cameras and capture the entire wind turbine (see Figure 3). The multi-view technique enables test engineers to obtain displacement and strain mode shapes of a structure. These strain mode shapes are used in the expansion algorithm to predict full-field strain all over the entire structure using a limited set of measurements.

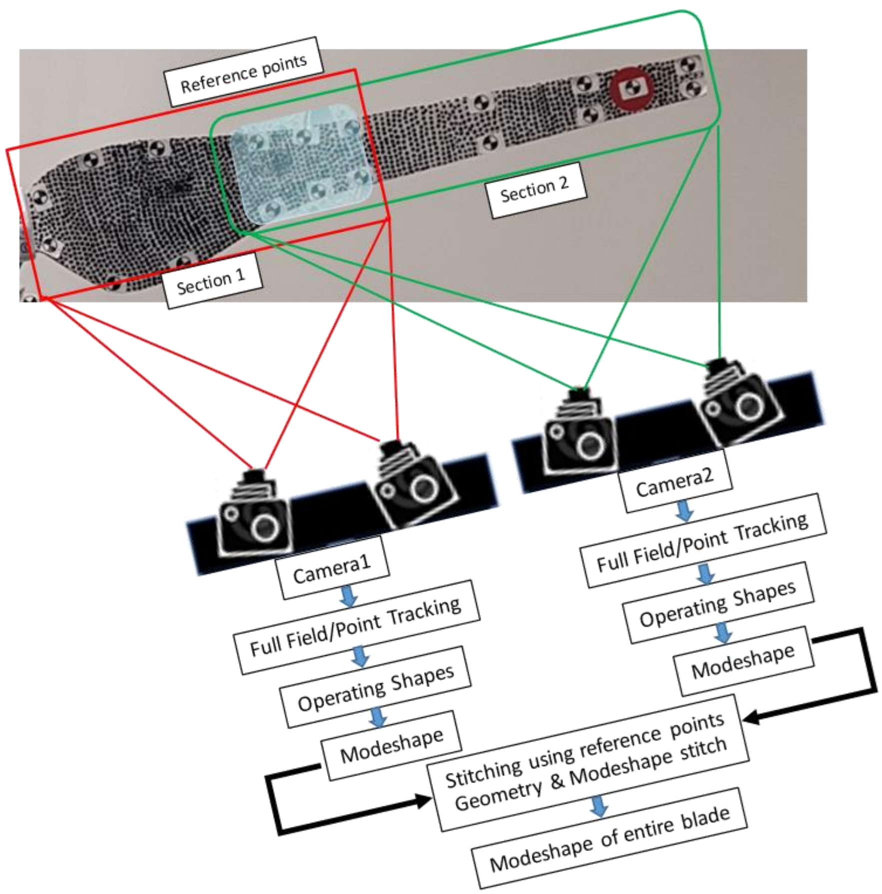

Figure 1. A flowchart showing the proposed technique for extracting operating mode-shapes of a beam using multiple views [22].

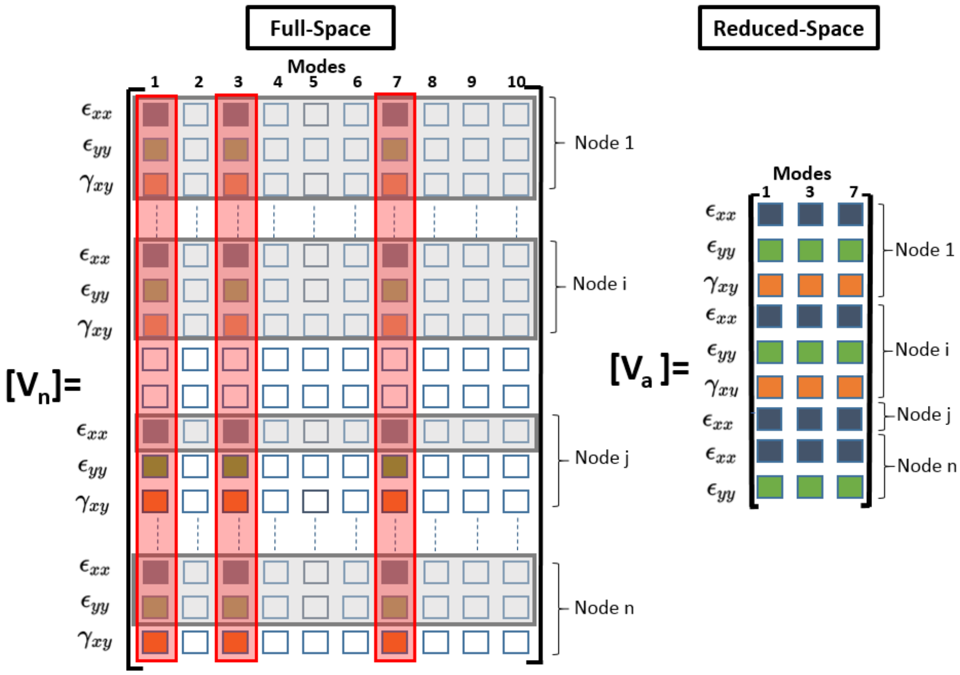

Figure 2. A schematic showing the full-field strain expansion reduction approach (SERA). In this schematic, [Vn] shows full-field strain mode shapes, and [Va] shows reduced mode shape matrix [23].

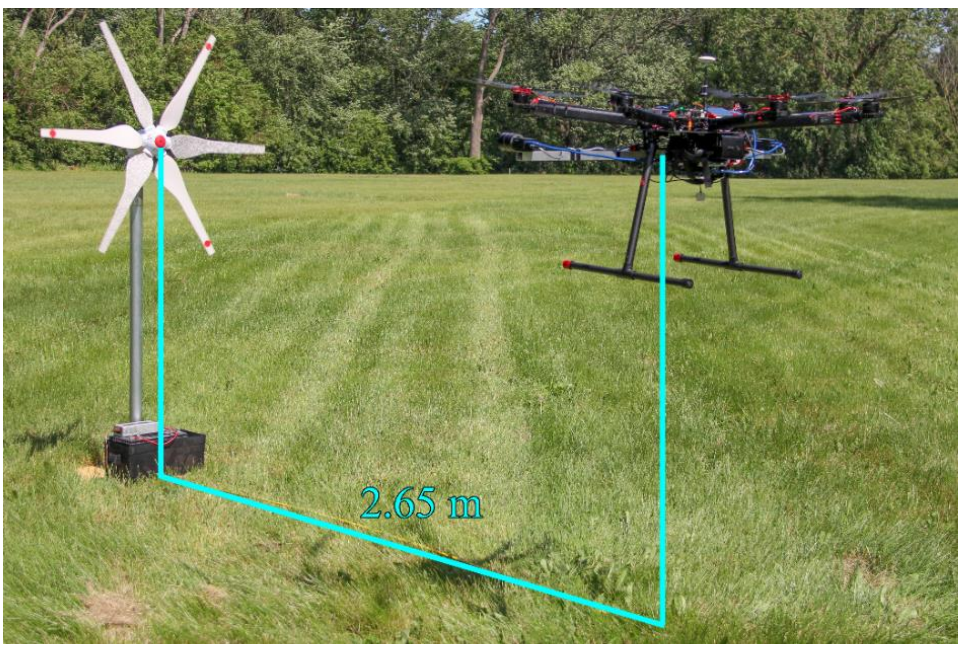

Figure 3. Data acquisition in the field using a flying drone

TEST SETUP AND MEASUREMENT

To show the merit of the proposed technique, a test was performed on a cantilever blade of the wind turbine and a turbine. The test setup for indoor measurement on the wind turbine and the cantilever blade is explained below.

Perform Multi-View DIC Measurement

The first step for digital twin development is to collect operating data from the wind turbine. In this work, we use digital image correlation to collect data. In order to rove the camera over the structure, we use a semi-autonomous drone.

The current structural health monitoring algorithms are based on using a limited set of data collected at a few discrete locations. The reliability of these methods depends on the location of the sensors placed. Recently, Digital Image Correlation (DIC) has been used to obtain the full-field dynamics of structures. However, a stereo camera system has a line of sight only on certain parts of a complex structure. Furthermore, using the DIC system for in-situ measurements is challenging. Baqersad et al. [21, 24] proposed a new technique to scale the DIC mode shapes using measured force and stitch the shapes in the frequency domain. The core concept behind this technique is to obtain the operating deflection shape of the structures having complex geometry (see Figure 1). The proposed technique works by stitching the operational deflection shapes of each section in the frequency domain rather than the time domain. The structure is excited with an unknown force using an impulse hammer, and the response is measured using a pair of DIC cameras. This technique utilizes a least-square minimization that facilitates the stitching and scaling of the operational deflection shapes extracted by roving the pair of DIC cameras around the structure.

The current work will use the multi-view technique but will take a step further and use the measured data to create mechanical models of structures. The vibration information can represent basic modes of vibration and will be processed to obtain numerical models that capture the dynamics of structures.

To perform the measurement, a speckle pattern is applied to the surface of the wind turbine (see Figure 4). A pair of cameras are used to collect data. The cameras capture the deformation of the wind turbine. The photos are processed using digital image correlation to obtain accurate displacement and strain from the collected images. Figure 5 shows the test setup for the cantilever blade test.

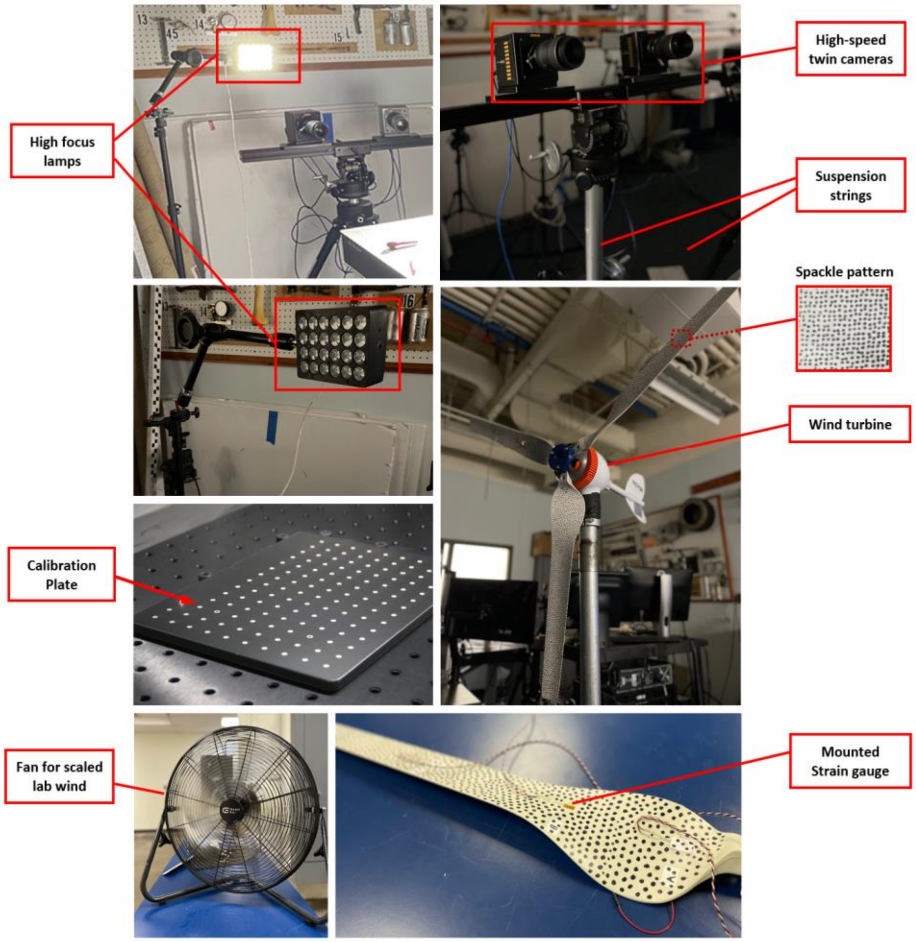

Figure 4. Experimental equipment for conducting the proposed image-based digital health monitoring, including time-dependent deformation data collection on blades of a wind turbine via a pair of high-speed DIC (digital image correlation) cameras, a Vevor turbine model FT-400, strain gauges, and a fan for the lab test wind.

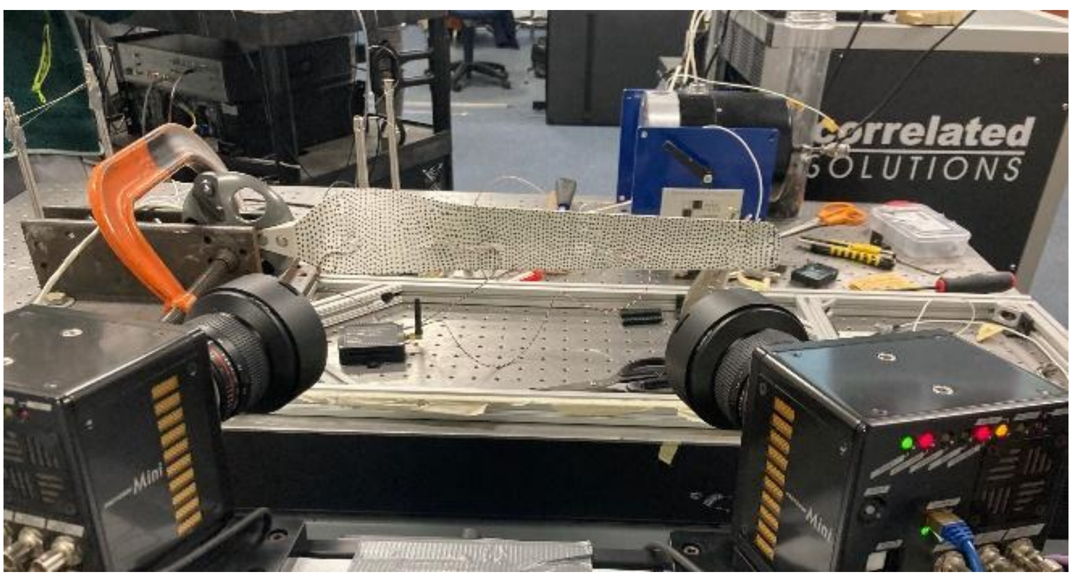

Figure 5. A photograph showing the experimental setup, including the test structure and cameras for the single cantilever blade measurement.

RESULTS FROM DIC

Figures 6 and 7 show the operating data for the turbine blade and the entire turbine, respectively. DIC can provide displacement and strain data on a wind turbine in operating conditions. This data will be used to develop a digital twin of the structure.

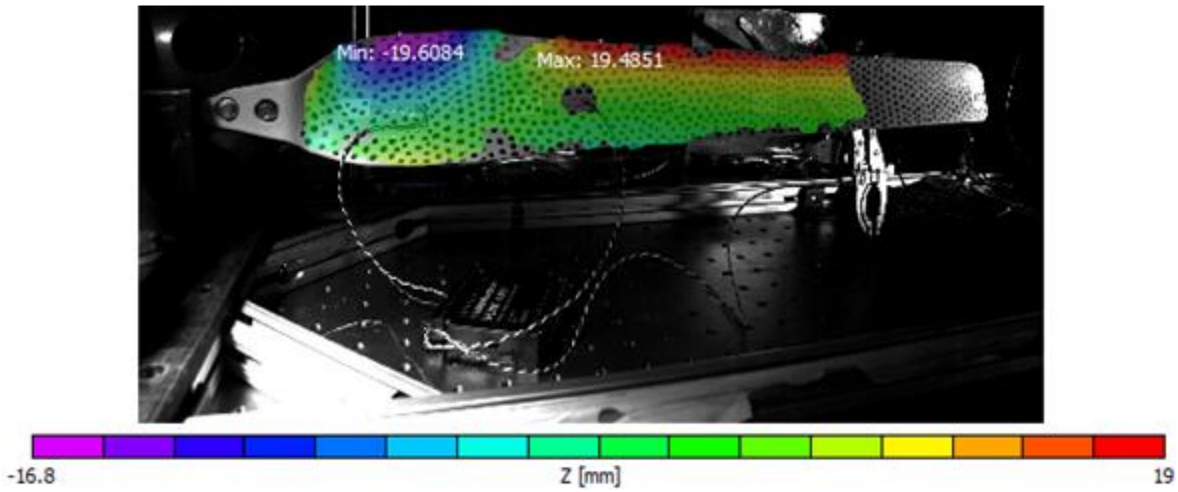

Figure 6. DIC results for the healthy blade in cantilever pluck test.

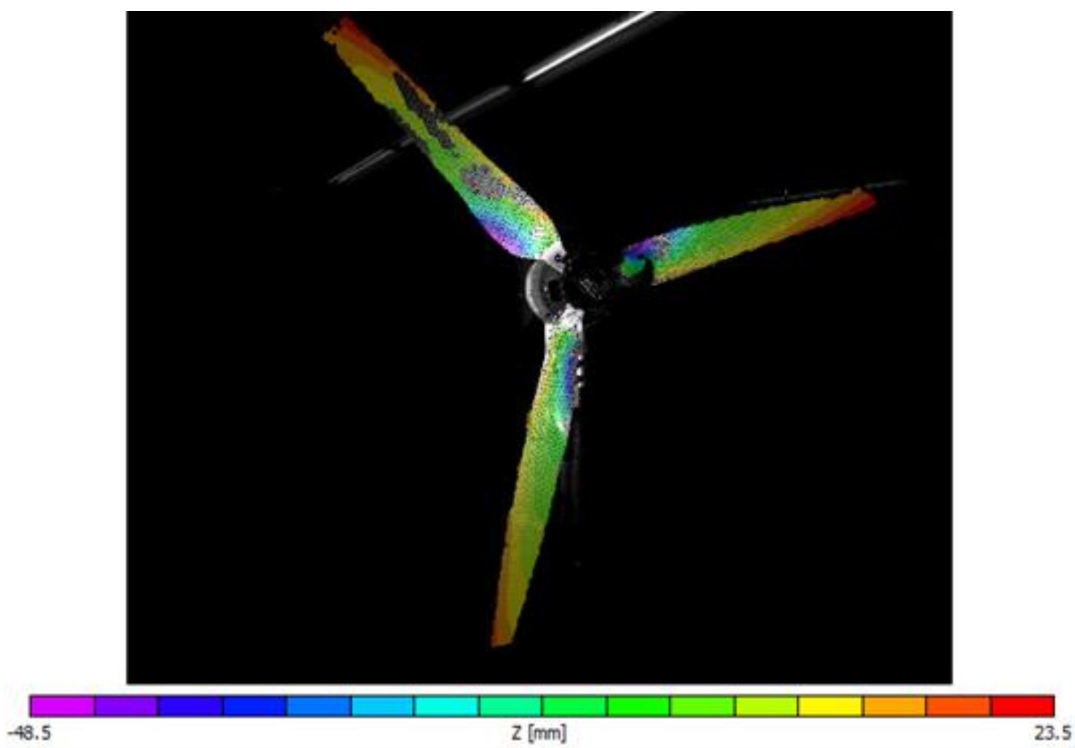

Figure 7. Deflections of rotating turbine measured using DIC

DIGITAL TWIN DEVELOPMENT USING MODAL EXPANSION

After obtaining the deflection of the wind turbine, the measured data is expanded using the modal expansion technique. The expanded measurements are used to obtain full-field strain and displacement data (see Figure 8). The displacement and strain data can be expanded in real-time, generating a digital version of the wind turbine. This data can be used for monitoring of the turbine.

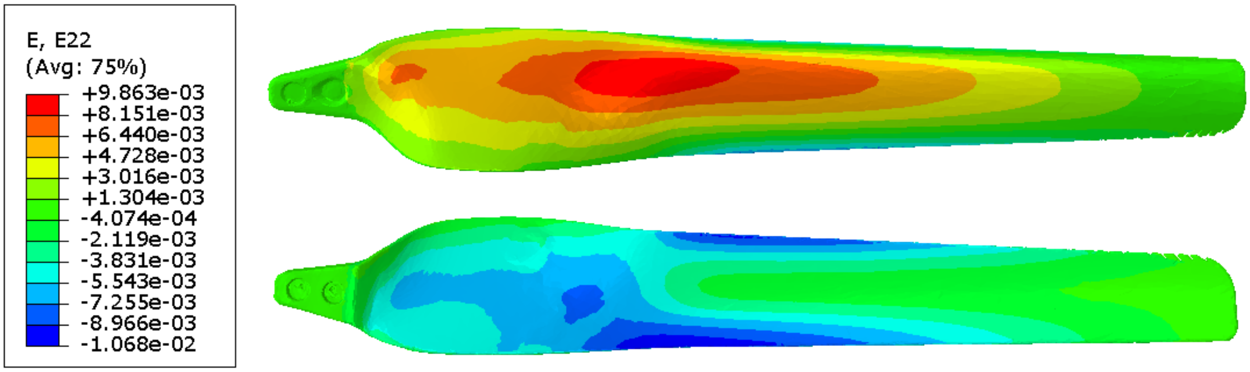

Figure 8. The strain on the digital twin of the wind turbine blade obtained by expanding the measured deflections and applying it to the finite element model

CONCLUSIONS

The current work shows that digital twins of wind turbines can be developed using a drone monitoring system. An application for this technique is when the full-field strain data for an operating system needs to be monitored while only a few strain gages can be mounted to the sample (e.g., wind turbine blades, tires, helicopter rotors, or vehicle chassis components). This technique can also be very effective when the finite element modeling of a structure is challenging (e.g., components made of composite materials). The strain mode shapes for the expansion can be extracted using a multi-view DIC system without the need to develop a finite element model. Using this approach, the strain mode shapes for a structure can be extracted in a test facility. The in-situ limited set of measurements can be performed using strain-gages or fiber optic sensors. The limited set of measurements is expanded using the strain mode shapes to extract full-field results for dynamic study, structural health monitoring, and fatigue analysis.

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