Full-field dynamic strain prediction on a wind turbine using displacements of optical targets measured by stereophotogrammetry

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ABSTRACT

Health monitoring of rotating structures (e.g. wind turbines and helicopter blades) has historically been a challenge due to sensing and data transmission problems. Unfortunately mechanical failure in many structures initiates at components on or inside the structure where there is no sensor located to predict the failure. In this paper, a wind turbine was mounted with a semi-built-in configuration and was excited using a mechanical shaker. A series of optical targets was distributed along the blades and the fixture and the displacement of those targets during excitation was measured using a pair of high speed cameras. Measured displacements with three dimensional point tracking were transformed to all finite element degrees of freedom using a modal expansion algorithm. The expanded displacements were applied to the finite element model to predict the full-field dynamic strain on the surface of the structure as well as within the interior points. To validate the methodology of dynamic strain prediction, the predicted strain was compared to measured strain by using six mounted strain-gages. To verify if a simpler model of the turbine can be used for the expansion, the expansion process was performed both by using the modes of the entire turbine and modes of a single cantilever blade. The results indicate that the expansion approach can accurately predict the strain throughout the turbine blades from displacements measured by using stereophotogrammetry.

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1. Introduction

For many complex structures, mechanical failure is not externally apparent and typically occurs at the interfaces between the structure's surface and the internal ribs or stiffening members. Health monitoring of wind turbines is usually performed by collecting real-time operating data on a handful of points using traditional sensors such as accelerometers or strain-gages located on the nacelle. Although wind turbines may stop operating because of damage in their blades, there are generally few to no sensors mounted in turbine blades. The loss of operation results in a loss of power generation and revenue for wind farm owners. Placing sensors on rotating structures is a physical challenge due to wiring, data transmission, and mass-loading effects. Therefore, a current area of interest to the wind and rotorcraft industries is how to monitor the condition of

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Nomenclature		$\{p\}$	modal participation vector
		$[U_a]$	reduced mode shape matrix
$\{x_n\}$	full-space displacement vector	$[U_a]^g$	generalized inverse of reduced shape matrix
$\{x_a\}$	reduced-space displacement vector	$[U_n]$	full-space mode shape matrix
$\{x_d\}$	displacement vector for deleted degrees of freedom	$[U_d]$	mode shape matrix for deleted degrees of freedom
$[M_a]$	reduced mass matrix	$[T]$	transformation matrix
$[M_n]$	full-space mass matrix	$[RTO_a]$	real-time operating data at reduced-space
$[K_a]$	reduced stiffness matrix	$[ERTO_n]$	expanded real-time operating data
$[K_n]$	full-space stiffness matrix		

rotating blades using non-contacting sensors that have distributed sensing capability over a large area, while not adding significant cost or affecting the performance of the structure. Stereophotogrammetry and three-dimensional point tracking (3DPT) have recently enabled new opportunities for blade inspection and structural health monitoring in wind turbines and helicopter blades. Our long-term research objective is to integrate a non-contact stereophotogrammetry technique with a new analytical structural dynamic approach to accurately predict the global (exterior surface and interior) dynamic strain (or stress) of rotating structures. The current lack of distributed measurement capability for rotating structures compounded with the inability to accurately assess the deformation and global strain (or stress) using a limited set of sensors has not been sufficiently addressed by the scientific community and provides the motivation for the research.

Within this work, the optical three-dimensional point-tracking (3DPT) measurement approach is used in conjunction with a recently developed modal expansion technique. These two approaches (empirical and analytical) complement each other and enable the prediction of full-field dynamic strain on the surface of the structure as well as within the interior points. Therefore, an introduction regarding these methods and a review of the previous efforts in these areas are summarized in the following sections.

1.1. Prior work related to photogrammetry

Three-dimensional (3D) digital image correlation (DIC) and three-dimensional point tracking (3DPT) are non-contacting measurement approaches that provide alternatives to traditional measurement sensors and LDVs. Both 3D DIC and 3DPT are based on stereophotogrammetry principles and rely on a pair of digital cameras to capture images of the structure over a period of time. For the DIC approach, speckled patterns are applied to a structure and can be used to obtain full-field displacement and strain over the entire area of interest. Likewise, 3DPT can be used to measure displacement at discrete points by mounting optical targets to the structure. DIC and 3DPT have matured over the last two decades and have been primarily applied to the field of experimental solid mechanics. However, more recently researchers have begun to exploit the optically based approach for measuring vibration and transient phenomena in turbine blades and rotors.

There have been several published papers that use photogrammetry to measure vibration in non-rotating and rotating turbine blades. Carr et al. showed that surface strain measured from strain-gages in a cantilevered wind turbine blade compared well with 3D DIC measurement for dynamic [1] and static [2] configurations. In another effort, strong correlations were shown between mode shapes of the blade extracted using 3DPT and mode shapes found by using other traditional approaches [3]. Helfrick et al. [4] proposed a method to use low speed cameras for measuring vibrations in rotating structures. High-speed cameras were used by Warren et al. [5,6] to measure vibrations in a small-scale rotating wind turbine but only a few operating deflection shapes could be determined. Lundstrom et al. [7] showed that appropriate rigid body correction for a rotating structure requires a sufficient number of points that are stationary with respect to each other within the field of view. In another work by Lundstrom et al. [8], operating deflection shapes of a wind turbine were extracted by applying a harmonic filter to the 3DPT measured data. A robust method for point tracking in rotating structures is suggested by Kaploe et al. [9]. One of the first works to use stereophotogrammetry for utility-scale wind turbines was performed by Paulsen et al. [10]. They performed a 3DPT measurement on a 500 kW wind turbine [10]. Following their work, Ozbek et al. [11–14] measured the displacement of retro-reflective optical targets on a 2.5 MW wind turbine.

3DPT has also been used for measurement of vibrations in helicopter rotors. Lawson [15] measured the vibrations of a small-scale flexible rotating blade assembly for helicopters. A full-scale measurement of a helicopter using photogrammetry was performed in the German-Dutch wind tunnel [16–18]. Following the German-Dutch wind tunnel measurement, another full-scale test on a helicopter was performed by NASA [19]. The use of retro-reflective targets on the "instrumentation pod" located above the rotor hub simplified their rigid body correction and mode extraction. The researchers could extract five operating shapes of blades in that test. The first outdoor field-test of a helicopter in flight using 3DPT was performed by Lundstrom et al. [20].