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Vibration-based damage detection in wind turbine blades using Phase-based Motion Estimation and motion magnification

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A B S T R A C T

Vibration-based Structural Health Monitoring (SHM) techniques are among the most common approaches for structural damage identification. The presence of damage in structures may be identified by monitoring the changes in dynamic behavior subject to external loading, and is typically performed by using experimental modal analysis (EMA) or operational modal analysis (OMA). These tools for SHM normally require a limited number of physically attached transducers (e.g. accelerometers) in order to record the response of the structure for further analysis. Signal conditioners, wires, wireless receivers and a data acquisition system (DAQ) are also typical components of traditional sensing systems used in vibration-based SHM. However, instrumentation of lightweight structures with contact sensors such as accelerometers may induce mass-loading effects, and for large-scale structures, the instrumentation is labor intensive and time consuming. Achieving high spatial measurement resolution for a large-scale structure is not always feasible while working with traditional contact sensors, and there is also the potential for a lack of reliability associated with fixed contact sensors in outliving the life-span of the host structure. Among the state-of-the-art non-contact measurements, digital video cameras are able to rapidly collect high-density spatial information from structures remotely. In this paper, the subtle motions from recorded video (i.e. a sequence of images) are extracted by means of Phase-based Motion Estimation (PME) and the extracted information is used to conduct damage identification on a 2.3-m long Skystream® wind turbine blade (WTB). The PME and phased-based motion magnification approach estimates the structural motion from the captured sequence of images for both a baseline and damaged test cases on a wind turbine blade. Operational deflection shapes of the test articles are also quantified and compared for the baseline and damaged states. In addition, having proper lighting while working with high-speed cameras can be an issue, therefore image enhancement and contrast manipulation has also been performed to enhance the raw images. Ultimately, the extracted resonant frequencies and operational deflection shapes are used to detect the presence of damage, demonstrating the feasibility of implementing non-contact video measurements to perform realistic structural damage detection.

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1. Introduction

Structural health monitoring (SHM) has been widely applied in a variety of applications over the past several years with a goal of improving reliability, achieving lower cost condition-based maintenance, performing damage prognosis, and eliminating unexpected catastrophic failures [1,2]. Several approaches have been adopted for structural damage detection, such as vibration testing [3], ultrasonic guided wave inspection [4,5], acoustic emission [6,7], thermal imaging [8], etc. In all SHM efforts, the identification of the healthy state of the structure is the very first step that later yields to a decision-making process to identify the presence of damage after processing the later measurements [9]. After data cleansing and normalization, the measurements undergo the process referred to as the feature extraction that preserves the damage sensitive properties of the acquired data and eliminates the redundant information that are not contributing to the decision-making process [9]. The decision-making procedure is then performed based on the extracted features. This stage oftentimes is accomplished by a human in the loop as an expert in order to detect the occurrence of the damage based on the extracted features. The process may also be handled automatically using machine learning, statistical data processing or other autonomous classification, and clustering algorithms [10].

Vibration-based SHM follows the above-mentioned procedure, i.e. the dynamic response of the structure is measured by means of instruments such as accelerometers or strain sensors, and the damage-sensitive features being used in vibration based SHM are extracted (e.g. resonant frequencies, damping, mode shapes or operating deflection shapes (ODS), or other dynamic sensor signal features) [3]. That being said, experimental and operational modal analysis (EMA and OMA) are the two widely adopted techniques used in structural dynamics identification to extract features employed in vibration-based SHM and the corresponding decision-making procedure [3], as well as being used for model updating and model validation in several applications related to aerospace, civil and mechanical systems [11,12].

For the vibration-based SHM approach, decision-making regarding the status of the system is made according to the changes in dynamic behavior of structures [13]. Sensor systems play a major role in both EMA and OMA approaches as well as other activities for structural dynamics identification. An ideal sensor system for modal analysis should be able to record the vibration information of the structure accurately with high spatial resolution without alternating the dynamics of the structure induced by mass-loading effects or changes to the stiffness. Accelerometers are precise sensors having a broadband frequency range of measurement and are relatively inexpensive, therefore are utilized widely for modal analysis. However, instrumentation of lightweight structures with accelerometers induces mass-loading effects, and can make unwanted changes to the dynamics of the structure. Despite the efforts of compensating the mass-loading effects, the accuracy of numerous mass cancelation methods is not satisfactory [14,15]. Although in some SHM/damage detection applications, where the mass-loading effect appears in the baseline, which makes it not a major concern, avoiding such effect is still a valuable advantage in many related system identification applications such as EMA and OMA. In addition, performing modal testing on large-scale structures with accelerometers can be highly time consuming and labor intensive because the installation of a large number of accelerometers on the structure and handling all the wiring and instrumentation is not always straightforward [16]. More importantly, current accelerometers are only able to measure the responses at discrete locations, and are not able to provide full-field spatial resolution, which is necessary in many situations such as mode shape curvature-based SHM techniques [17]. The maintenance of large-scale infrastructures equipped with accelerometers or other conventional discrete sensors, is also costly and this is another major drawback of using accelerometers or strain gages, especially for long-term SHM applications.

Laser vibrometers are capable to record the response of structures without any mass-loading effects and do not alter structural stiffness [18,19]. In addition, high spatial resolution may also be achieved if the laser vibrometers are empowered with precise scanning capabilities. However, laser scanning vibrometers are relatively expensive and the response of the structure is measured sequentially which increases the measurement time considerably if a high spatial distribution is required. Likewise, for structures with very large or low-frequency displacements, the scanning laser measurement systems are not always effective.

Digital video cameras combined with image and video processing algorithms provide another non-contact approach for structural measurements [20–26]. Compared to laser vibrometers, digital cameras are low-cost and capable to make simultaneous full-field measurements. Recently, high resolution and high-speed (frame rate) digital video cameras in conjunction with stereo-photogrammetry approaches, such as 3D digital image correlation (3D DIC) and 3D point tracking (3DPT), have been utilized to perform modal analysis and strain analysis on large-scale industrial structures [27–34]. Although 3D DIC and 3DPT provide smooth mode shapes with high accuracy, these methods generally require a speckle pattern or high contrast markers mounted or painted on the surface of the structure. Surface preparation for large-scale structures could be enormously time-consuming or even not practical if the structure has an extreme operating environment. Considering the high computational burden of 3D DIC and 3DPT, processing the collected image data in real time is not currently viable except for low frequencies. As an alternative, phase-based computer vision algorithms have recently gained more attention for structural motion estimation, and system dynamics identification to avoid the above-mentioned surface perpetration and decrease the size of data associated with 3D DIC and 3DPT that may lead to less computational effort as well. In 2015, Chen et al. [35–37] utilized phase-based motion estimation (PME) combined with a motion magnification algorithm to extract the resonant frequencies and operational deflection shapes of several lab scale benchmark structures, including a cantilevered beam and a pipe test specimen. The main advantage of PME is that surface preparation is no longer necessary for the analysis, and the algorithm is capable of extracting the approximate motion information using the natural features of the