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Large-area photogrammetry based testing of wind turbine blades

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ABSTRACT

An optically based sensing system that can measure the displacement and strain over essentially the entire area of a utility-scale blade leads to a measurement system that can significantly reduce the time and cost associated with traditional instrumentation. This paper evaluates the performance of conventional three dimensional digital image correlation (3D DIC) and three dimensional point tracking (3DPT) approaches over the surface of wind turbine blades and proposes a multi-camera measurement system using dynamic spatial data stitching. The potential advantages for the proposed approach include: (1) full-field measurement distributed over a very large area, (2) the elimination of time-consuming wiring and expensive sensors, and (3) the need for large-channel data acquisition systems. There are several challenges associated with extending the capability of a standard 3D DIC system to measure entire surface of utility scale blades to extract distributed strain, deflection, and modal parameters. This paper only tries to address some of the difficulties including: (1) assessing the accuracy of the 3D DIC system to measure full-field distributed strain and displacement over the large area, (2) understanding the geometrical constraints associated with a wind turbine testing facility (e.g. lighting, working distance, and speckle pattern size), (3) evaluating the performance of the dynamic stitching method to combine two different fields of view by extracting modal parameters from aligned point clouds, and (4) determining the feasibility of employing an output-only system identification to estimate modal parameters of a utility scale wind turbine blade from optically measured data. Within the current work, the results of an optical measurement (one stereo-vision system) performed on a large area over a 50-m utility-scale blade subjected to quasi-static and cyclic loading are presented. The blade certification and testing is typically performed using International Electro-Technical Commission standard (IEC 61400-23). For static tests, the blade is pulled in either flap-wise or edge-wise directions to measure deflection or distributed strain at a few limited locations of a large-sized blade. Additionally, the paper explores the error associated with using a multi-camera system (two stereo-vision systems) in measuring 3D displacement and extracting structural dynamic parameters on a mock set up emulating a utility-scale wind turbine blade. The results obtained in this paper reveal that the multi-camera measurement system has the potential to identify the dynamic characteristics of a very large structure.

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1. Introduction

As wind turbine blade manufactures are pushing the envelope of design and moving toward larger scale blades, the need for effective non-destructive evaluation (NDE) and a better understanding of blade dynamics increases. The current state of practice to inspect wind turbine blades relies on traditional sensors (e.g. strain gages, string potentiometers, and accelerometers) that provide information at a number of discrete points. [1–4]. However, the complex dynamic response of these sizable blades cannot be quickly or easily measured using a limited set of mounted accelerometers. Placing transducers on a utility-scale wind turbine blade is labor intensive, requires a multitude of sensors and hardware, and can also introduce electrical noise to the measured signal due to the extensive wiring. A typical 50 m utility-scale blade requires ~200 gages (costing $35k–$50k), takes ~3 weeks to set up. Performing accurate modal tests requires numerous, low frequency, and high sensitivity accelerometers that can be very expensive (e.g. $300–$1400 per sensor) along with the associated signal conditioners. If a non-contact measurement system was available that could measure full-field deflections and distributed strain, it would be possible to streamline the blade testing process by eliminating instrumentation and sensors and saving set up time (e.g. typically 3–4 technicians working for 2 days). Techniques such as using a scanning laser Doppler vibrometer (SLDV) are limited to sequential measurement (i.e. one point at a time) and to obtain information at many points the laser measurements must be tested in series [5–7]. Additionally, measuring very large displacements as found on wind turbine blades using a SLDV is not possible because the large motions of the structure cause the targeted laser position to move on the structure. However, digital image correlation (DIC) can measure the full-field response of the structure and is not sensitive to large deformations. Stereo-photogrammetry in the context of this paper uses 3D DIC and 3DPT techniques. These approaches provide the ability to collect 3D dynamic measurements at many more points on a structure compared to conventional testing using strain gages, accelerometers, or displacement sensors. However, for large scale structures within a test facility or even outdoors, the use of stereo-photogrammetry to measure large dimensions may be limited by the camera separation or the required working distance to capture the field of view of interest. Owing to a stereo-vision system's limited field of view, large-scale test articles and structures with complex curvatures need to be measured from many different viewing directions. The knowledge gained by developing a multi-camera system will lead to a measurement system that can significantly reduce the time and cost associated with strain gage instrumentation; thereby, reducing the time required for blade certification and levelized cost of energy (LCOE). The current lack of multi-camera stereo-photogrammetry measurement to accurately assess the operating deflection shapes of large structures with complex geometry has not been sufficiently addressed by the scientific community and provides the motivation for this work.

This paper extends the understanding of 3D DIC measurement capabilities by evaluating the performance of a multi-camera 3D DIC system in which data obtained with conventional DIC systems are stitched together in a universal coordinate system. The primary objectives are to quantify the performance of conventional 3D DIC by conducting a full-field experiment on a large area (i.e. wind turbine blade) and evaluate the performance of a multi-camera DIC system in extracting the modal parameters on a test structure. A review of the previous efforts in these areas is summarized in the following sections. An example of the types of measurements that can be acquired using DIC over a large area is shown for a utility-scale wind turbine blade in Section 2. Following, how multiple fields of view are stitched together and an analysis of the associated errors of the approach are presented for a wind turbine blade mock up.

1.1. Prior work related to photogrammetry

Full-field measurement using non-contact techniques to extract desired dynamic characteristics of structures led researchers to develop optical measurement systems. Pattern interferometry, laser Doppler interferometry, and photogrammetry are three types of optical methods [8]. The interferometry techniques such as ESPI and DSS, developed prior to DIC system, have been employed to measure full-field response of structures subjected to dynamic and static loading. The interferometry techniques use an interference fringe pattern created by the superposition of two coherent light patterns and measure the displacement between these patterns.

Auweraer et al. [9] used pulsed-laser holography, or electronic speckle pattern interferometry (ESPI), to perform vibration testing. Zanarini [10] used ESPI for a broad frequency band vibration measurement and compared the performance of ESPI with SLDV and DIC [5,6]. In other attempts ESPI technique was employed to obtain full-field vibration measurements in the fatigue behavior assessment of mechanical components by means of spectral approaches [11–13]. A laser Doppler vibrometer (LDV) scans each point sequentially; therefore compared to 3D DIC and ESPI, a LDV may not have the consistency in the measurement as the physical excitation or the structure changes over time during a measurement.

Using either a LDV or interferometry techniques is not well suited to making measurements on utility-scale wind turbine blades because of the very large deformations these structures exhibit during fatigue testing. Additionally, both of these approaches are susceptible to noise measurement, which can be problematic when testing in a field setting or location with ground vibrations. Stereo-photogrammetry is better suited for making measurements at lower frequencies when the structures' displacements are large [14]. A fair amount of research has been conducted to improve stereo-photogrammetry techniques, three-dimensional digital image correlation (3D DIC) and three-dimensional point tracking (3DPT) as an alternative to conventional point-wise and contacting measurement sensors. Both 3D DIC and 3DPT are non-contact image based techniques that rely on a series of images taken with two digital cameras to track the motion of an object in three dimensions. Although 3DPT is not technically a full-field measurement technique because it measures motion at discrete