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Optical Non-contacting Vibration Measurement of Rotating Turbine Blades II

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ABSTRACT

Identifying the structural dynamics of rotating components can be difficult. Often times, structural dynamic measurements are obtained while the structure is in a static configuration. There are differences that exist in the structural behavior when comparing these statically performed tests and the dynamic characteristics when in operation. In order to evaluate the actual system while in operation, slip-rings are used during testing with measurements made at only a very few selected points. But this slip-ring configuration can be problematic, suffer from measurement noise and the attached sensors can obscure the true dynamic response due to mass loading and aerodynamic effects.

3D digital image correlation (DIC) has been used to capture the out-of-plane motion on the surface of a small scale rotating fan blade. This work extends prior efforts, by quantifying the performance of the optical measurement on a 46 in (1.17m) diameter, rotating wind turbine. The optical measurements are made using DIC (10,000+ measurement points) and dynamic photogrammetry (providing dozens of effective measurement locations). The motion of the turbine as measured using DIC, photogrammetry and accelerometers is compared at several discrete points. The proposed measuring approaches via DIC and dynamic photogrammetry enable full-field dynamic measurement and monitoring of rotating structures in operation.

INTRODUCTION

Although stereophotogrammetry has been used for many years in the field of solid mechanics to measure displacement and strain, only very recently has the technique been exploited for dynamic applications to measure vibration. The DIC technique is able to measure the non-contacting static and dynamic 3D motion of virtually any surface. Prior to testing, the photogrammetric principles of triangulation and bundle adjustment [1] are used in the determination of a camera pair's relative position and to account for the internal distortion parameters of each lens. The calibration process is essentially a ray-tracing process to find unique intersection points, similar to how a GPS system triangulates coordinates. A speckle pattern is applied to a test object prior to imaging for DIC while dynamic photogrammetry tracks high-contrast, circular targets. Examples of each can be seen in Figure 1.

After calibration occurs, a series of image pairs are taken during the course of an experiment. The first pair of images is set as the reference stage to which all subsequent stages are compared. The images are divided into overlapping facets (or subsets), typically 10-20 pixels square. For correlation to work, the corners of each facet must be matched within the surrounding "fingerprint" of light intensity values. This is why a speckle pattern is applied to the object prior to imaging. Software is able to recognize and track a specific point on a series of images through a correlation process which is well documented for two-dimensional [2, 3] and three-dimensional [4, 5] measurements. By tracking discrete points in images taken by a stereo pair of cameras and applying photogrammetric principles, shape and strain can be measured. Subsequently, displacement, velocity, and acceleration can be computed. For cameras with 1280 x 1024 pixels, the overall accuracy of the system can be conservatively stated as 1/30,000 the field of view [6]. Multiple image sets provide a progressive measurement of structural deformation and strain.

The method is extremely robust and has wide dynamic range that is not affected by rigid body motions, ambient vibrations, etc. As long as non-blurred images can be captured, 3D coordinates, displacements, and strains can be measured on virtually any surface. Because the technique is non-contacting, it is possible to measure the full-field vibration of a rotating object without significant mass loading or the use of slip rings.

EXPERIMENTAL RESULTS

The test article used was a 46 inch (1.17m) diameter Southwest Windpower Airbreeze wind turbine, mounted to the shaft of a commercial electromechanical fan motor. During non-rotational testing, traditional modal tests and forced normal mode testing were performed using accelerometers and a laser Doppler vibrometer as references for the performance of the optical measurement techniques. Rotating tests were also performed using accelerometers mounted at the tips of the three blades and monitored via a slip ring.

Figure 1. Example of prepared measurement surfaces: speckling for DIC and circular retroreflective targets used for dynamic photogrammetry.

Stationary Testing

Initially, a three-shaker multiple input, multiple output (MIMO) modal test was performed. A laser Doppler vibrometer was used to measure the response at roughly 18 points per blade. Three shakers were used to more evenly distribute the input energy to all three blades of the turbine. Also, using one shaker on each blade allowed for a more appropriate set up where the shaker-stinger interaction with the structure was minimized [7]. The shaker mounting points are indicated by the three large, circular red dots shown in Figure 2; the measurement points are specified by small green squares. Once frequency response functions (FRFs) were calculated, a frequency domain polynomial curvefitter was used to extract modal parameters and mode shapes.

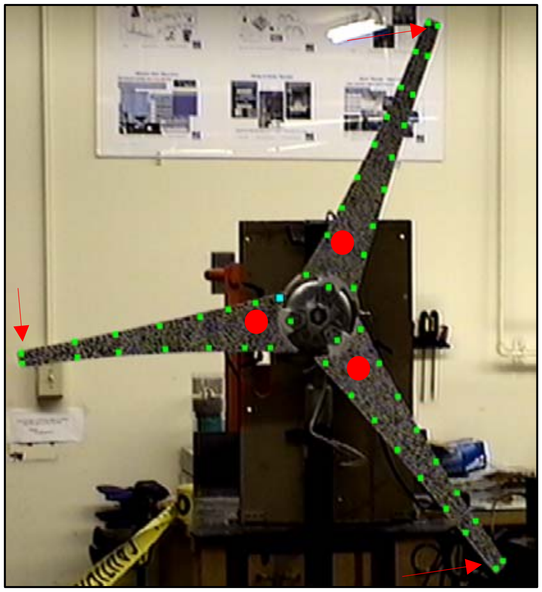

Figure 2. Full view of the wind turbine with measurement locations.

Subsequently, forced normal mode testing (FNMT) was performed to excite the structure such that it exhibited single degree of freedom behavior at the first two modes [8]. The full-field mode shapes for each frequency were obtained by using the data extracted via DIC measurements. The displacement and phase were then used as feedback to appropriate the input forces more accurately and drive the turbine in a forced normal mode. Figure 3 displays an overlay of the extracted MIMO mode shapes (wire-frame) and the shapes measured using the DIC system (ARAMIS^{TM}) [9]. In these tests, the motion of approximately 6,000 data points per blade was tracked, providing a high-resolution depiction of how the rotor was moving. After several iterations of force appropriation adjustment, the normal mode shapes were produced. For modes 1 (16.8 Hz) and 2 (17.2 Hz), MAC values of 99.3% between the laser vibrometer measured mode shape and the DIC measured mode shape were obtained using forced normal mode testing.

Rotational Testing

Past work has shown that dynamic photogrammetry can be used to measure the motion of large rotating wind turbines while in operation using relatively high speed cameras (measured at 20~30 times the rotational frequency) [10]. For tests herein, a camera pair operating at 500 frames per second (FPS) was used to monitor the rotor as it was being driven by the electric motor. A separate data acquisition system was synchronized with the optical system and measured the accelerometer outputs via a slip ring at 10 kHz (20 times the camera frame rate). The accelerometers were placed at the tips of the 3 blades, indicated by red arrows in Figure 2. The frequency of rotation was set arbitrarily to approximately 10 Hz.

Figure 4 depicts a typical output from the dynamic photogrammetry software (PONTOS^{TM}) used [10]. 3D motion of any visible target can be tracked from stage to stage; the plot shows the position in the x-direction as a function of time. Each oscillation is 120^{o} out of phase with the other two, and the amplitudes are all nominally equal, as expected. Additionally, motion in the y- and z-directions can be tracked. The z-axis is defined by the vector about which the rotor turns. Figure 5 displays the time response at one of the blade tips in the z-direction (out-of-plane) measured by the optical system. The synchronized accelerometer measurement is displayed in Figure 6.

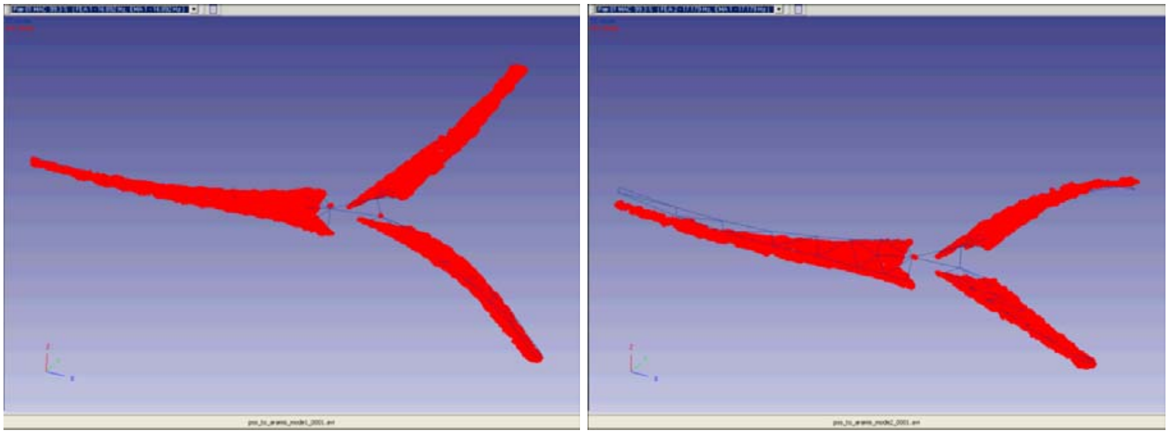

Figure 3. MIMO and FNMT DIC shapes for (a) mode 1 – 16.8 Hz; (b) mode 2 – 17.2 Hz.

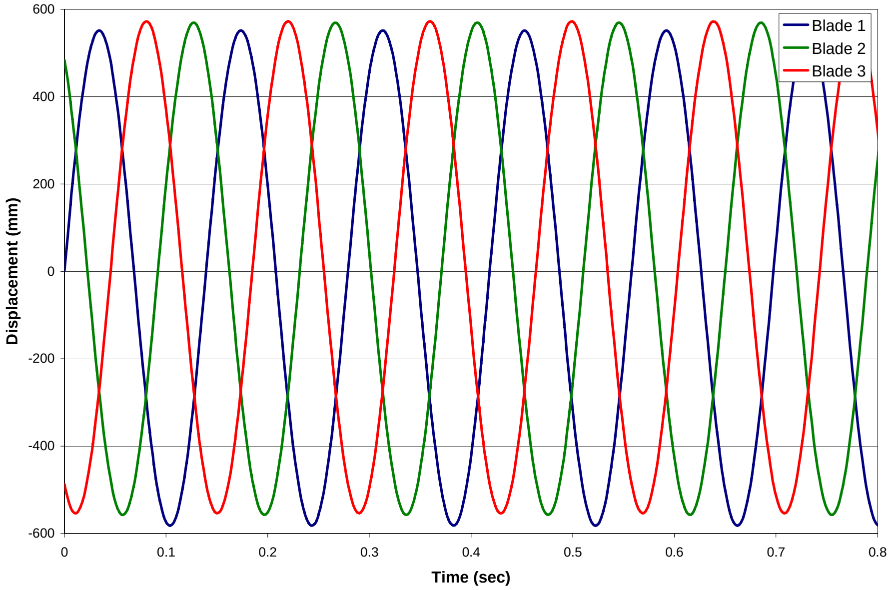

Figure 4. Typical dynamic photogrammetry results, x-displacement.

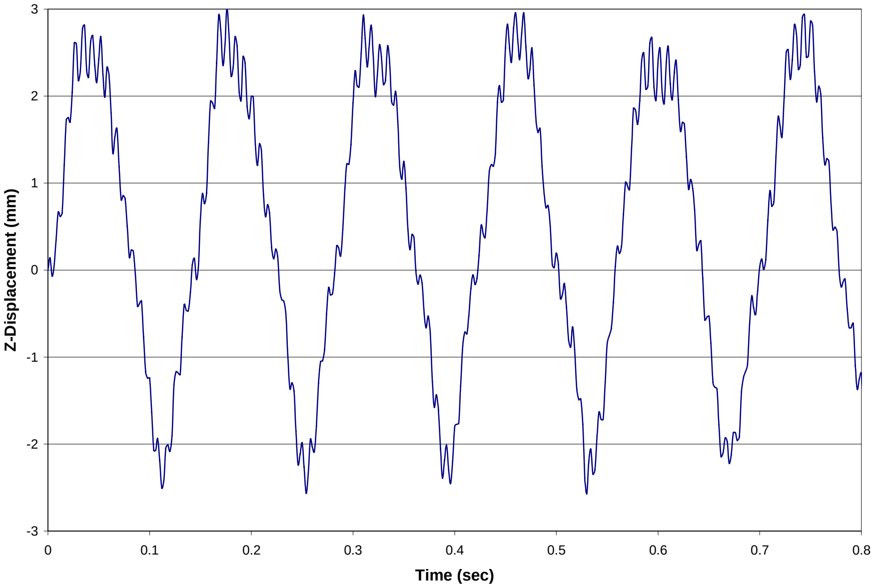

Figure 5. Blade 3 Results, z-displacement.

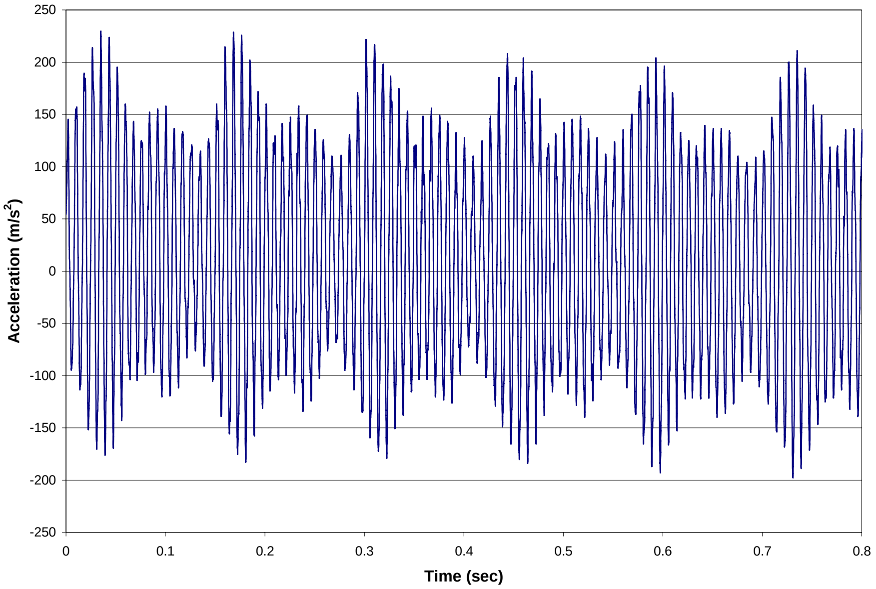

Figure 6. Blade 3, synchronized accelerometer measurement.

Once the time domain data was acquired, flattop windows were applied and FFTs were performed to compare the data in the frequency domain. Figure 7 displays an overlay of autopower spectra from measurements at the tip of one of the blades using dynamic photogrammetry and an accelerometer up to 150 Hz. The initial results are fairly consistent but differences are apparent. Known issues that must be considered are: the cross-axis sensitivity of the accelerometers; noise from the slip ring; the noise floor of the optical system; potential nonlinear joint characteristics; and the useful ranges of both sensors. These discrepancies have not been addressed and are the subject of future work.

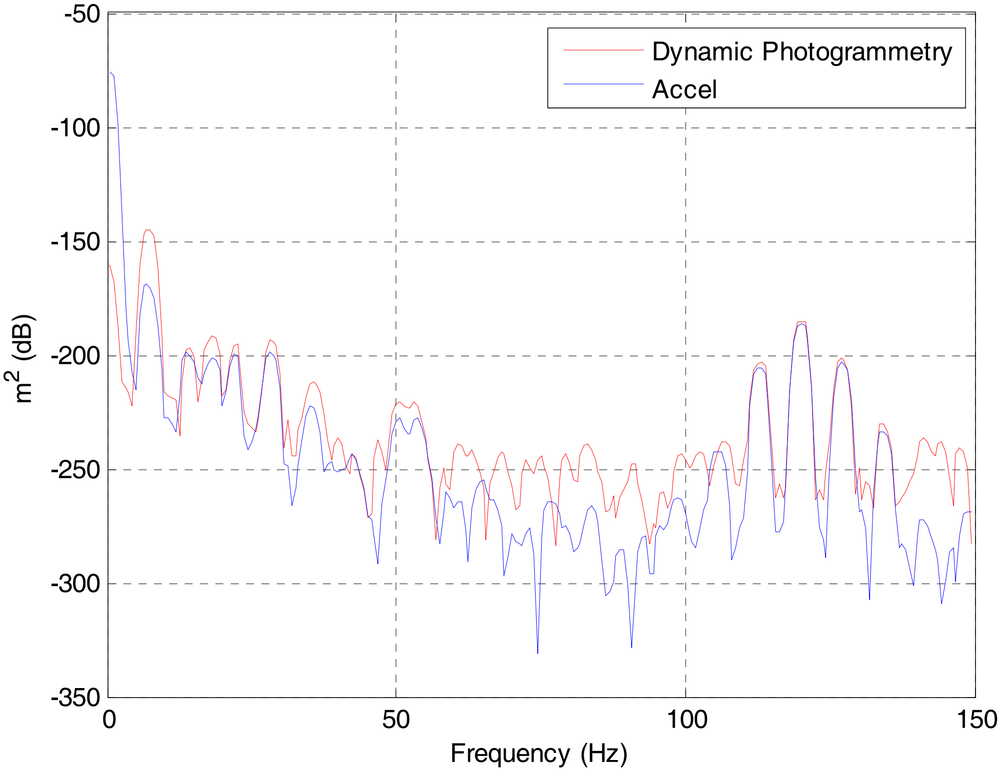

Figure 7. Blade 3 – Autopower spectra overlay for dynamic photogrammetry and accelerometer results.

All the measurements above are shown, in general, for only one particular point on the structure. A significant advantage of PONTOS is that all of the measured points are collected simultaneously which allows for 3D visualization of the motion. This enables a very clear understanding of the structure deformation while rotating. Figures 8 and 9 display one step of the time-varying displacement vector fields for the xy – and z – components, respectively, superimposed on an image of the wind turbine studied. Shown are vectors of specific length scaled to the motion as well as color coded to allow for easy visualization of the data. In Figure 9, one can clearly see that at this point in time, the top and right hand blades are roughly 180^o out of phase while the left blade is deformed very little.

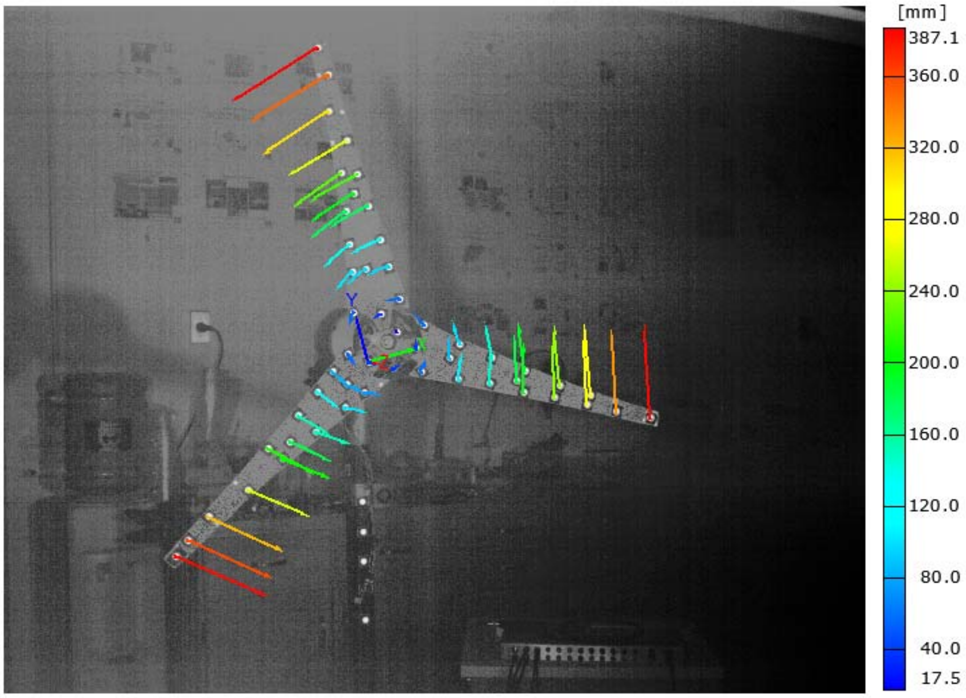

Figure 8. XY-component motion of the rotor shown in color to represent vector length.

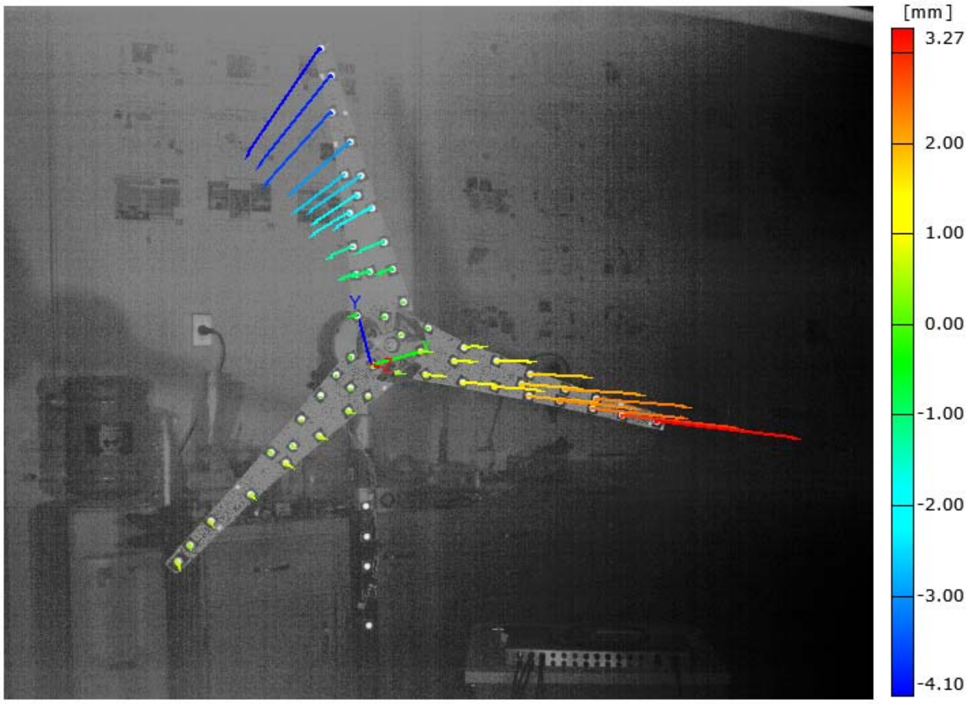

Figure 9. Z-displacement vector field shown in color to represent vector length.

CLOSING REMARKS

Optical based measurements have been shown to be consistent with more traditional measurement techniques such as accelerometers and laser Doppler vibrometers while measuring both rotating and non-rotating structures. When used in conjunction with forced normal mode testing, DIC can provide a high-fidelity measurement of mode shapes at tens of thousands of points. Likewise, dynamic photogrammetry allows for the measurement of the full-field motion of the rotating blade at numerous points, without contact. MAC values greater than 99% were obtained for the first two modes of the wind turbine studied. Dynamic photogrammetry was used to measure the rotor while spinning and yielded results consistent with collocated accelerometers. Slight discrepancies are evident and will be addressed in future work. While these initial results are encouraging, more studies must be completed while working towards understanding the strengths, weaknesses, and useful ranges of these systems. Additional measurements need to be made to validate and confirm these preliminary findings.

ACKNOWLEDGEMENTS

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