MONITORING THE DYNAMICS OF AN OPERATING HELICOPTER ROTOR USING 3D DIGITAL STEREOPHOTOGRAMMETRY

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ABSTRACT

The measurement of vibration data on rotating structures (e.g. helicopters rotors or wind turbines) during operation has historically been a challenge. Conventional sensors are difficult to implement (due to wiring and power requirements) and can induce mass loading effects. Moreover, cabling and data transmission through slip rings or wireless devices can introduce noise into the measured data. In this paper, stereophotogrammetry is investigated as an alternative to conventional sensors for measuring the vibration of a rotating helicopter rotor. Dynamic point tracking is used to measure displacements at numerous points distributed along a 10.1-meter diameter rotor blade of a Robinson R44 helicopter. A pair of high speed cameras was installed on a long camera bar that was calibrated by using an array of coded targets placed on the ground. The displacement of 22 optical targets mounted to the blades was measured while the helicopter rotor was spinning with the helicopter on the ground and hovering. Operational modal analysis of the measured data was performed revealing the dominant contribution of the structural modes to the operating deflection shapes. The helicopter rotor motion was dominated by harmonics of the blade passage frequency, however some non-harmonic operating deflection shapes were also observed. This paper provides a description of the experiment performed along with lessons learned while performing the test. This study reveals that stereophotogrammetry has significant potential as a robust non-contacting measurement technique for monitoring dynamic behavior of rotating helicopter rotors or wind turbine blades.

1. INTRODUCTION

As a non-contacting measurement technique, stereophotogrammetry lends itself to the measurement of the operational dynamics of large, rotating systems because it avoids the cabling difficulties of wired transducers and can be easily scaled up to larger systems by increasing the size of the targets applied to the surfaces of the structure. Stereophotogrammetry also offers the ability to collect dynamic measurements in 3D on many more points on a structure, more easily, than compared to a typical multi-channel transducer data acquisition (DAQ) system.
The primary challenge when making photogrammetry measurements of rotating structures involves the large angular rotations that result when a turbine or rotor is spinning. To appropriately extract the small vibratory structural motion from the large rigid body movements and interpret the effects of the harmonics is not trivial. Helfrick et al. [1] proposed a method to use low speed cameras for measuring vibrations in rotating structures. High-speed cameras were used by Warren et al. [2, 3] to measure vibrations in a small scale rotating wind turbine but only a few operating deflection shapes could be determined. Lundstrom et al. [4] showed that appropriate rigid body correction (RBC) for a rotating structure, a sufficient number of points that are stationary with respect to each other needs to be used. In another work by Lundstrom et al. [5], operating deflection shapes of a wind turbine-like structure were extracted by applying RBC using the nodes of the non-rotating mode shapes in conjunction with a harmonic filter to the 3DPT (three dimensional point tracking) measured data. A robust method for point tracking in rotating structures is suggested by Kaploe et al. [6].

One of the first works to use stereophotogrammetry for large wind turbines was performed by Paulsen et al. [7, 8]. The stereophotogrammetric measurement technique has been used to collect dynamic operating data on large wind turbines including the measurement of the dynamic behavior of a 500 kW wind turbine during an emergency stop from 24 rpm to 0 rpm. Following their work, Ozbek et al. [9-12] measured the displacement of retro-reflective optical targets on a 2.5 MW Nordex N80 wind turbine with an 80-meter tower height and rotor diameter. Within their work, the researchers describe the efforts to sufficiently illuminate this large structure and collect stereophotogrammetric operating data. The structure was illuminated with high-power light emitting diode (LED) strobe lights synchronized with the camera pair by a central computer. The papers also describe the domination of harmonic components in the measured dynamics hindering modal parameter estimation from power spectra.

3DPT has also been used for measurement of vibrations in helicopter rotors. Lawson [13] measured the vibrations of a small-scale flexible, rotating, blade assembly for helicopters. Several experiments have been performed in which stereophotogrammetry was applied to the dynamic measurement of helicopter rotors. In 2001, a wind tunnel test was performed in the Large Low-Speed Facility of the Dutch-German wind tunnel on a four meter, four-bladed rotor system; the stereophotogrammetry system utilized four cameras. Flapwise, edgewise and torsional data was collected on all four blades of the rotor [14-16]. The work also describes efforts to properly determine the rotor center of rotation and transformation of the coordinate system from the wind tunnel coordinate system to a more convenient rotor coordinate system. Following the German-Dutch wind tunnel measurement, another full-scale test on a helicopter was performed by NASA at the National Full-Scale Aerodynamic Complex (NFAC) at NASA Ames Research Center in Moffet Field, California [17]. Their paper describes the procedure and results for the second of three stereophotogrammetry tests on a UH-60A four-bladed rotor system. 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 5 operating shapes of blades in that test. The full-scale stereophotogrammetric helicopter test presented in this work was performed in the field (outside) with sunlight as the primary source of illumination. In addition, only a single pair of high-speed cameras was used in the data acquisition and the blades of the main rotor were realistically loaded as the helicopter hovered. A more detailed discussion of the test setup and the results can be found in [18].

2. EXPERIMENTAL SETUP AND PROCEDURE

The full-scale test article was a Robinson R44 helicopter with a 10.1-meter diameter main rotor. According to the R44 pilot’s operating handbook [19], the main rotor tip speed is 215 m/s at 102% of the operating rate. With a main rotor circumference of 31.7 meters, the
rotational frequency of the main rotor is 6.8 Hz. Optical data was to be acquired with a pair of Photron SA2 FASTCAM high-speed cameras that can record 2048 x 2048 pixel images and were controlled by a portable laptop workstation. The frequency rate raised several concerns regarding performing the full-scale filed test using only natural sunlight. Several pretests were performed with a model helicopter to insure the adequacy of natural sunlight to properly illuminate the structure and to determine a proper shutter time to minimize blurring at the rotor extents. A shutter time of 1/8000 second was selected for the full-scale helicopter test. The Robinson R44 Raven helicopter used in this experiment can be seen in Figure 1.

![Figure 1. Robinson R44 Raven with dimensions obtained from the pilot’s operating handbook [19].](image)

Several pieces of custom equipment were developed for this test including a 3.7-meter camera bar, a series of 7.4E-2-meter diameter vinyl targets to temporarily adhere to the helicopter blades to track the motion of the blades and a series of coded targets to perform a large-scale calibration prior to data acquisition. Images of the large-scale calibration can be seen in Figure 2.

![Figure 2. Large-scale calibration procedure for full-scale helicopter test showing a) coded target array with J. Baqersad shown as a scale reference; b) positions for the boom lift platform for calibration; c) calibration picture acquisition from the platform (T. Lundstrom and C. Niezrecki); d) camera bar and high-speed cameras mounted to boom lift.](images)
The large-scale calibration shown in Figure 2 was performed with a Genie S60 boom lift. The 16 coded targets were mounted to the tarmac in a square, 4 x 4 array with 10.1-meter sides as shown in Figure 2a and a series of pictures were taken with the high-speed cameras at different elevations and orientations as shown in Figure 2b-c. Measurements were taken between several targets to scale the calibration. Very high accuracy measurements (1/60,000 of observed field of view) can be performed using photogrammetry technique. A detailed description of the calibration procedure and technique details can be found in [18].

A series of 22 uncoded vinyl targets were mounted to the top surface of the helicopter main rotor in the configuration shown in Figure 3. The targets were evenly distributed across the blades to see both flexing and twisting operating deflection shapes (ODS). Figure 3 also shows the subsets of uncoded targets (blade 1, hub, blade 2) used to examine the rotor dynamics with and without rigid body correction (RBC). Subsequent rigid body corrections performed on this data utilized the “hub” measurement points to track/remove rotor rigid body motion. ODSs were determined without the application of RBC.

Five operational data sets were collected for the main rotor of the Robinson R44 helicopter. Two data sets were collected with the helicopter grounded at 50% (3.4 Hz idle rotation rate) and 102% (6.9 Hz operating rotation rate) operating speeds. A pair of high-speed cameras was lifted diagonally above the main rotor of the helicopter with the boom lift to achieve a working distance of approximately 12 meters. The height of the cameras above the ground was approximately 14 meters. Data was acquired for both operating frequencies with a camera sample rate of 250 frames per second (fps), with a 1/8000 second shutter time, but only the 6.9 Hz data set will be discussed in this paper.
Three additional data sets were collected above and below the helicopter with the helicopter hovering above the ground. Two data sets were acquired from above the main rotor and a final data set was acquired below the helicopter, unfortunately, the high-speed cameras lost calibration during the acquisition of the fifth data set; the fifth data set will not be discussed in this paper. The data acquisition for the grounded and hover data sets can be seen in Figure 4.

3. INITIAL DATA PROCESSING

Only three data sets (full-speed grounded, hover 1 (fs = 1080 fps) and hover 2 (fs = 250 fps), will be presented in this work as the quality of these data surpassed that of the other two data sets. The description of the initial processing procedure follows.

The series of photo pairs for the three data sets were imported into PONTOS\textsuperscript{TM} [20] with the calibration file and appropriate settings for the ellipse quality, ellipse radius and maximum allowable intersection error to allow the software find all 22 measurement points in all data stages. The values for these parameters for the three helicopter tests is shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Max. Intersection Error (pixels)</th>
<th>Min. radius (pixels)</th>
<th>Ellipse qual. (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-speed, grounded</td>
<td>0.70-0.80</td>
<td>2.0</td>
<td>0.30</td>
</tr>
<tr>
<td>First hover, fs = 250 fps</td>
<td>1.00</td>
<td>2.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Second hover, fs = 1080 fps</td>
<td>0.80-0.90</td>
<td>1.8</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 1: Parameter values for three helicopter tests

Prior to performing any additional processing, the $X$, $Y$, $Z$ coordinates for all analysis points for all data stages were exported as an ASCII file for each of the five PONTOS\textsuperscript{TM} projects. Initially, the orientations/positions of the global coordinate systems are arbitrary relative to the measurement points. To effectively process all data, the center of rotation and a best-fit swept rotor plane was established. The center of rotation was calculated as the centroid of the point clouds using the maximum number of integer main rotor rotations that occurred in each data set. The composite point clouds for the three data sets were also used to determine the best fit plane through which the rotor swept for each data set. A singular value decomposition (SVD) was performed to determine the principal coordinates of each composite point cloud yielding best-fit coordinate systems for each data set. The SVD can be calculated according to:

$$ A = U E V^T $$

where $U$ and $V$ are orthogonal matrices and $E$ is a diagonal matrix of singular values. The eigenvectors of $A A^T$ are the columns of $U$ and the eigenvectors of $A^T A$ are the columns of $V$. The third row of the $V$ matrix is a unit vector normal to the best-fit plane of each point cloud. Using:

$$ V = \begin{bmatrix} u_i & v_i & w_i \\ u_j & v_j & w_j \\ u_k & v_k & w_k \end{bmatrix} $$

The equation for the best-fit plane can be written according to:

$$ Z_{bfp} = -\frac{w_i}{w_k} X - \frac{w_j}{w_k} Y $$
Equation (2) was used to plot the best-fit planes for all three data sets. The center of rotation and best-fit plane for the full-speed, grounded test can be seen in Figure 5. Similar plots/calculation were performed for the remaining two data sets.

The calculated centers of rotation and best-fit swept plane unit vectors for the three data sets can be seen in Table 2.

<table>
<thead>
<tr>
<th>Center of rotation (mm)</th>
<th>Best-fit plane unit vector (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Full-speed, grounded</td>
<td>-744.3</td>
</tr>
<tr>
<td>First hover, f_s = 250 fps</td>
<td>122.0</td>
</tr>
<tr>
<td>Second hover, f_s = 1080 fps</td>
<td>-25.4</td>
</tr>
</tbody>
</table>

Table 2: Center of rotation coordinates and best-fit plane unit vector for three data sets.

The center of rotation coordinates and best-fit plane unit vectors were used to perform coordinate system transformations in PONTOS™. This coordinate system transformation helps to reduce the dominance of the fundamental harmonic in measured data by reducing the misalignment between the rotor axis of rotation and the global Z axis. A description of the preliminary results for the three data sets processed follows.

4. EXPERIMENTAL RESULTS

Prior to the calculation of power spectra and extraction of ODSs, the operating data for the grounded, full speed and first and second hover tests was processed in PONTOS™ to track the motion of the optical targets in three dimensions, perform coordinate transformation, and process several data sets with rigid body correction to better observe the flexible motion of the rotor blades with respect to the hub. Several plots can be seen in Figure 6 showing rotor tips displacements versus time for three data sets processed with and without rigid body correction. The sampling frequency is listed for the first and second hover tests.

From Figure 6a, the fundamental harmonic is not readily apparent in the “no RBC” plots for tip points 1 and 22 as the helicopter was grounded and the main rotor exhibited only small rigid body movements. The application of RBC to the full-speed, grounded data set resulted in some amplitude attenuation. The “no RBC” displacement-time traces in Figure 6b and Figure 6d exhibit well-defined fundamental harmonics; these harmonics appear to change amplitude over time as the main rotor moves during the helicopter hover. As shown in Figure 6c and Figure 6d, the application of RBC using the rotor hub to track the rotor motion resulted in significant attenuation of the fundamental harmonic.
The displacement-time data for the full-speed grounded and second hover tests ($f_s = 250$ fps) was passed through a 40 Hz low pass filter and double differentiated to yield acceleration-time data. The data was converted to Type 58 Universal File Format (UFF) for further processing within LMS Test.Lab 10A. Crosspower spectra were calculated and Operational POLYMAX was used to estimate modal parameters at stable poles. Tip points 1 and 22 were used as references. The stability diagram and extracted ODSs for the full-speed, hover test is shown in Figure 7. Only data with 250 fps sampling rates were used to yield sufficient frequency resolutions (maximum frame count of 1361).
As shown in Figure 7, ODSs were initially extracted for the first five harmonic frequencies. Clearly, the data was dominated by harmonic content. Stable poles can also be seen at non-harmonic frequencies; three poles were extracted at 12.60 Hz, 19.27 Hz and 24.69 Hz independently from the harmonic poles shown above the stability diagram in Figure 7. At this point it is unclear whether the two flexible (12.60 Hz and 19.27 Hz), non-harmonic poles are true ODSs/frequencies of the helicopter rotor at full-speed. Currently, the stable pole at 24.69 Hz exhibiting rigid body motion is not fully understood and requires further study.

The stability diagram and extracted ODSs for the second hover test \( f_s = 250 \text{ fps} \) is shown in Figure 8.

Similar to that shown in Figure 7, stable poles were readily found as shown in Figure 8 for the first five harmonic frequencies. In addition, stable poles could also be seen at several non-harmonic frequencies including: 12.35 Hz, 19.24 Hz, 24.66 Hz, 32.59 Hz and 36.99 Hz. Currently, the stable poles at 24.66 Hz and 36.99 Hz exhibiting primarily rigid body motion are not fully understood and require further study.
A shape and frequency comparison between three, non-harmonic ODSs between the full-speed, grounded and second hover tests can be seen in Table 3.

<table>
<thead>
<tr>
<th>Full-speed grounded (fs = 250 fps)</th>
<th>Second hover test (fs = 250 fps)</th>
<th>MAC</th>
<th>Percent Freq. diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.60 Hz</td>
<td>12.35 Hz</td>
<td>0.64</td>
<td>1.98 %</td>
</tr>
<tr>
<td>19.27 Hz</td>
<td>19.24 Hz</td>
<td>0.79</td>
<td>0.16 %</td>
</tr>
<tr>
<td>24.69 Hz</td>
<td>24.66 Hz</td>
<td>0.97</td>
<td>0.12 %</td>
</tr>
</tbody>
</table>

Table 3: Modal assurance criterion (MAC) comparison and percent frequency difference between full-speed, grounded and second hover (fs = 250 fps) tests.

As shown in Table 3, the shape similarity (MAC) between the 12.60 Hz and 12.35 Hz poles was fairly low at 0.64. In contrast, the remaining two shapes exhibited high similarity with MAC values of 0.79 and 0.97, respectively. In addition, the frequencies for the three, non-harmonic pole comparisons are nearly identical.

Much of the difficulty encountered in the estimation of modal parameters at non-harmonic stable poles was due to the dominance of high-amplitude harmonic content in the operating data. In addition, as stereophotogrammetry remains static with respect to the measured structure in contrast to measurement transducers mounted directly to the surface of the structure, the quality of the measurement is highly dependent on the selection of a convenient coordinate system and prior work has shown that the application of RBC can artificially constrain the structure being measured distorting extracted ODSs [5, 18, 21].

Figure 8. Stability diagram for second hover test (fs = 250 fps) with ODSs at harmonic and non-harmonic frequencies.
5. FUTURE WORK
To further process operating data from the helicopter, a modal impact test should be performed to determine the resonant frequencies and shapes for the structure without rotational effects. In addition, high amplitude harmonic content was present in the helicopter operating data and this made the extraction of operating deflection shapes quite difficult. Future work will include the collection of operating data from the helicopter main rotor at a number of operating frequencies including a static modal impact test. In addition, the exploration/development of a robust harmonic filter may improve the ODS extraction results for rotation systems. Several harmonic filtration techniques have already been developed by Groover et al. [22], Peeters et al. [23] and Randall et al. [24].

6. CONCLUSION
Operating data was successfully collected from the main rotor of a Robinson R44 helicopter in both grounded and hovering states using stereophotogrammetry techniques. A technique was presented to determine the center of rotation and perform coordinate transformation on the displacement data to present the flapwise displacement data most effectively. Displacement-time data was present for the rotor tip points with and without the application of RBC showing the attenuation of much of the fundamental harmonic for three data sets. Several non-harmonic ODSs were extracted from operational power spectra calculated from acceleration data.

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REFERENCES