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BLADE DEFORMATION MEASUREMENT OF A MODEL-SCALE ROTOR SYSTEM USING A SPR SYSTEM WITH IR CAMERAS

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ABSTRACT

A Stereo Pattern Recognition (SPR) system with infrared (IR) camera was applied to measure the deformation of model-scale rotor blades. Twelve IR cameras were installed on the ceiling of the open-jet test section of the low speed wind tunnel, Korea Aerospace Research Institute (KARI), and 103 reflective markers were installed on the upper surface of the blades, hub center, and non-rotating body. In order to initialize measurement coordinate system, calibration was performed using L-shape calibration frame with known X, Y coordinates, then the reference coordinates for the markers were acquired and used for analyzing flap, lead-lag, and torsion deformation from the test data. Wind tunnel test was performed at hover and forward flight conditions with advance ratios 0.1, 0.2, and 0.3. Optical images were acquired with the frame rate of 209 Hz and the shutter speed of 7,000 Hz. Image data were continuously acquired along azimuth angles; not synchronized to a specific azimuth angle. Therefore measurement time is relatively short compared to the measurement with synchronization to specific azimuth angles. The collected data were post-processed by spectral analysis and curve fitting after measurement. The blade deformations with respect to azimuth angle and radial position were successfully estimated through data processing. The averaged standard deviations for flap, lead-lag and torsional deflections are 0.41 mm, 0.72 mm and 0.48 degree respectively.

1. INTRODUCTION

In the development of a rotor system, an understanding of the aerodynamic characteristic and the structural response of blades is essential. However the prediction of the aeroelastic behavior of rotor blades under the unsteady air-loads is complicated. Therefore experimental deformation measurement has been and continues to be an important method to supplement analytical result for identifying the characteristics of a rotor system. The measurement technique for structural three-dimensional shapes with high accuracy is attractive to engineers in many fields. Various kinds of optical methods have been applied to shape estimation including interferometry, photogrammetry, and profilometry [1]. The optical shape estimation technique has a great advantage in the measurement of rotating structures because of its non-contact characteristics. There have been several studies for the shape measurement for the rotating blades; Fourier transform profilometry (FTP) [2], projection Moiré interferometry (PMI) [3], projected grid method (PGM) [4], and stereo pattern recognition (SPR) [5, 6]. One of the most well-known applications of optical method to the measurement of rotating rotor blades is HART II (2nd Higher Harmonic Control Aeroacoustic Rotor Test) program which utilized SPR measurements. The SPR measurement can provide us rigid body motion as well as elastic deformation with high accuracy.

In the optical measurement, the images can be affected by the brightness of the test environment. In some cases, it is required to measure the images in dark environment. But, if we use the infrared (IR) camera, it is possible to measure the images in brighter condition. In the measurement of rotating system, synchronization with azimuth angle should be considered as well. If we measure the images synchronized with azimuth angle, it is easy to extract average data at that location. However it will take much more time if we need data at many azimuthal locations. Therefore, in this study, a continuous measurement method along the azimuth angle was used to obtain the blade deformation data with high azimuth resolution.

In this study, an SPR system with IR cameras was applied to the blade deformation measurement. Data were continuously acquired with the frame rate slightly mismatched to the rotating speed, not synchronized with a specific azimuthal position. In total, 103 reflective markers were used, and the blade deformations with respect to azimuth and radial position were estimated through data processing. In addition to blade deformation, measurement of the blade pitch control angle was also performed.

2. SYSTEM CONFIGURATION

2.1. SPR system

The SPR system applied to the blade deformation measurement is *Eagle Motion Capture System* of Motion Analysis Corporation. The SPR system consists of 12 IR cameras which have IR ring-light and IR filters in order to detect 750 nm reflected rays from markers on the blades. The components of the system are listed in Table 1.

The system has maximum frame rate of 2,000 fps (frame per second) and maximum shutter speed of 30 kHz; the specification is summarized in Table 2. The static uncertainty is defined as an root-mean-square error value when measuring known marker position from 5 m distance.

Table 1 Components of SPR system

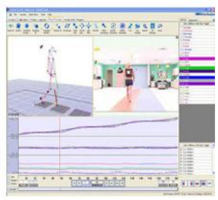
Digital camera w/ IR ring-light (12ea)	
Ethernet switch (2ea) & Power hub (2ea)	
Control & DAQ PC	
Calibration Jig (L-frame & wand set)	
Software suite	

Table 2 System specifications

Resolution	1280 x 1024 pixels
Frame rate	500 fps @ 1280 x 1024 1,000 fps @ 1280 x 485 2,000 fps @ 1280 x 242
Shutter speed	Max. 30,000 Hz
Static uncertainty	0.5 mm (from 5 m distance)

2.2. Measurement setup

The model-scale rotor system used in this study is 4-bladed articulated rotor system and the general properties are given in Table 3.

Table 3 Rotor properties

Properties	Values
No. of blades	4
Radius	1.129 m
Chord length	0.079 m
Solidity	0.088
Lock number	9.08
Nominal tip speed	225 m/s

The rotating test stand was installed in the low speed wind tunnel of Korea Aerospace Research Institute (KARI), which has exchangeable closed and open-jet test sections as shown in Figure 1. In order to minimize the influence of SPR systems on the wind flow and other operating and measurement systems, the SPR cameras are installed on the ceiling and placed in circular positions as shown in Figure 2. The height of the cameras is 3.7 m from hub center and radius of camera placement is 1.85 m.

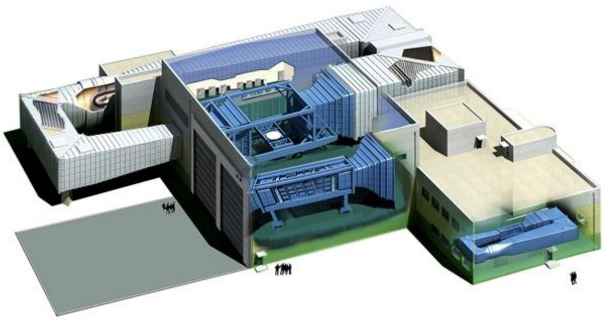


Figure 1 Low speed wind tunnel of KARI

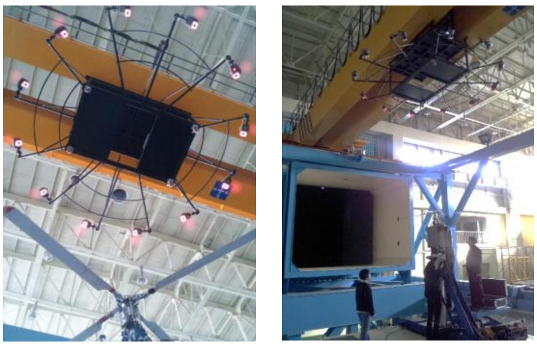


Figure 2 Camera installation in wind tunnel

In order to acquire 3-dimensional position data of markers, the SPR system should be calibrated in known coordinate system. The L-shape calibration frame was used as shown in Figure 3. It was positioned in parallel with rotor disk plane and the coordinates of calibration markers were measured from rotor hub center to generate global coordinate system having an origin at hub center.

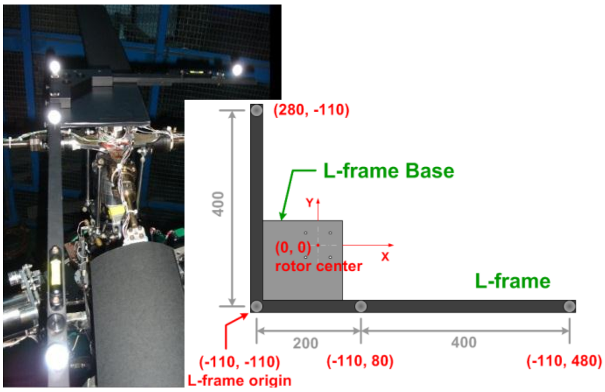


Figure 3 Calibration frame

Basically, the coordinate of the marker can be evaluated by two images taken by two cameras at different positions. However if we use more cameras, we can reduce the possibility of missing the marker position. Twelve cameras were installed at the beginning, but the images from two cameras were not good compared with other ten cameras' during the measurement campaign. Therefore ten cameras were practically used for deflection measurement.

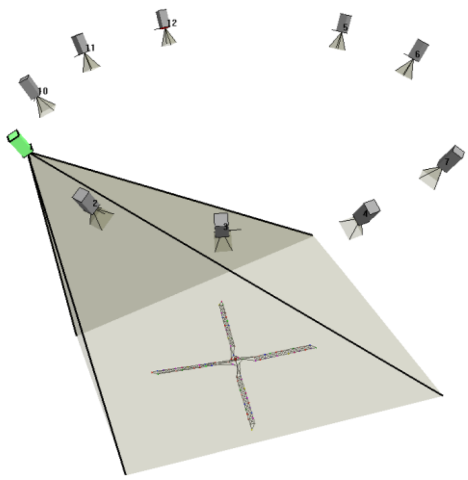


Figure 4 Field of view covering rotor plane

All cameras were inclined to the hub center, and each camera has field of view covering entire rotor plane as shown in Figure 4. Ideally, each camera should capture all markers on the blades; however blade tip markers are far from some cameras. Even in the worst cases, it was found that at least 6 cameras can capture the blade tip marker as in Figure 5.

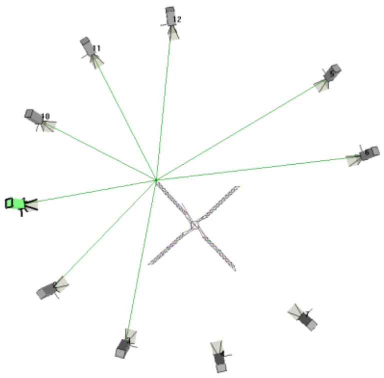


Figure 5 Cameras that can capture the tip marker

3. TEST SETUP

3.1. Markers' locations

In order to specify the locations of markers, the following capabilities were taken into account.

- Identifying blade number
- Identifying "0" azimuthal position
- Calculating azimuth angles of each blade
- Calculating pitch angle at the blade root
- Calculating blade flapping, lead-lag, and torsional motions

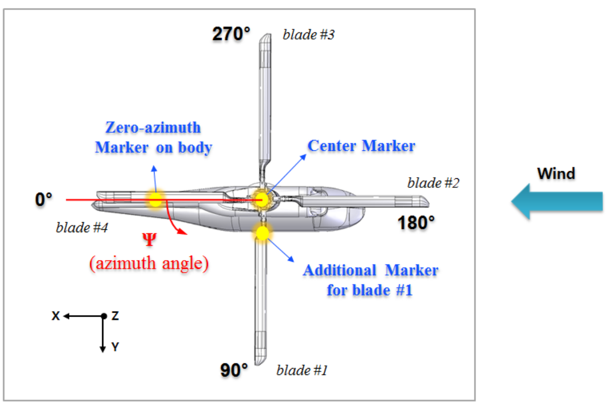


Figure 6 Reference markers for identifying azimuth angle

Azimuth angle was calculated using the reference markers on the nonrotating fixed body and blade no. 1 was marked with an additional marker as shown in Figure 6. The other three blades could be identified using the relative position to the blade no. 1. When the blade no. 4 is passing the azimuth of 0 degree, blade 1, 2, and 3 are passing the locations of 90, 180, and 270 degree, respectively.

Figure 7 shows the markers on the sleeves and pitch horns, which enables extraction of pitch angles of blades. The marker no. 2 is attached on top of the pitch horn and it is connected to pitch link. The pitch angle was estimated by the position of the marker no. 2 representing the displacement of pitch link.

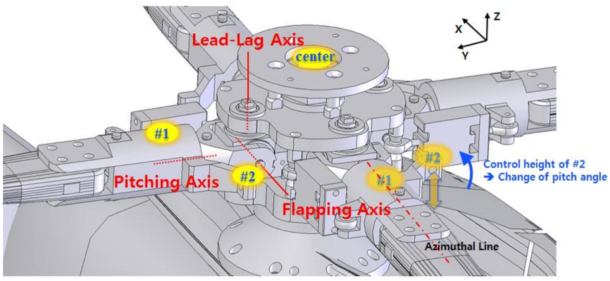


Figure 7 Markers for blade pitch measurement

For measuring the blade motion, markers are installed on the blade upper surface along the leading edge and trailing edge lines as shown in Figure 8.

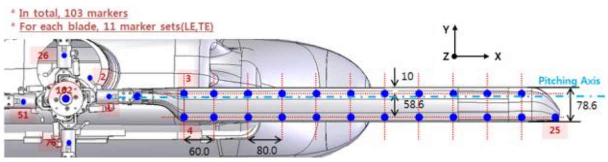


Figure 8 Markers for measuring the blade motion

First, blade pitching axis was calculated at each radial location of leading edge and trailing edge marker pairs. Then flapping and lead-lag motions were extracted from the z-dir. and y-dir. motions of pitching axis. Torsional deformation was calculated from the change of angle constituted by leading edge and trailing edge markers.

$$(x,y,z)_{PA} = \frac{(x,y,z)_{LE} \cdot l_{PA\_to\_TE} + (x,y,z)_{TE} \cdot l_{LE\_to\_PA}}{l_{LE\_to\_TE}}$$

$$\text{flapping} \quad d_{\beta} = z_{PA} - z_{PA,offset}$$

$$\text{lead-lag} \quad d_{\zeta} = y_{PA}$$

$$\text{torsion} \quad \Delta\theta = \tan\left[\frac{(z_{LE} - z_{LE,offset}) - (z_{TE} - z_{TE,offset})}{y_{LE} - y_{TE}}\right] - \theta_0$$

3.2. Reference data

Stationary position data for unloaded single blade and assembled rotor system were measured as shown in Figure 9 and used as reference data for motion analysis. First, a blade was laid down on the floor for identifying undeformed shape, and then pitching axis position relative to leading edge and trailing edge were estimated. After blade installation, marker position at the sleeves and pitch horns were measured for evaluation of initial blade installation angle.

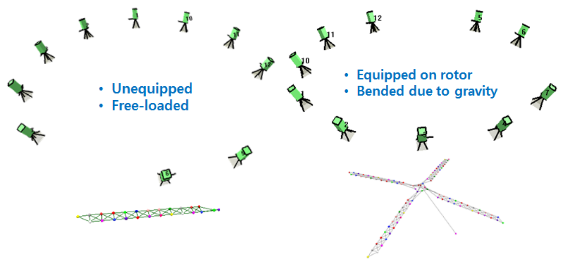


Figure 9 Reference data measurement

3.3. Test condition

Wind tunnel test was performed at hover and forward flight condition with advance ratios 0.1, 0.2, and 0.3. The nominal tip speed is 225 m/s as in Table 3; however the test was performed at reduced rotating speed, 57% NR (128 m/s), because of excessive vibration of rotor test stand. The wind tunnel test condition is given in Table 4. Trim was performed to get the target thrust and zero rolling and pitching moments.

In optical measurement system, we can adjust frame rate and shutter speed for good images. The frame rate can be synchronized to azimuthal steps to acquire images at specific locations. In this case, several images at the same position can be obtained to produce averaged data. However it takes much time to acquire data with high azimuthal resolution. And the rotating speed can vary during the test, so synchronization to specific azimuth angle is not easy.

In this study continuous acquisition with constant frame rate was applied with the support of reference marker for identifying azimuth information. At each test, totally 6,270 images were acquired during 30 seconds with 209 Hz frame rate. The acquired data produced sufficiently much amount of points which could be considered as almost continuous signal. Another parameter which should be properly selected to get good images is shutter speed. The selected shutter speed was 7,000 Hz; which was selected by considering the blurring error compared to a pixel size.

Table 4 Wind tunnel test condition

Test No.	Shaft angle (degree)	Advance ratio	Thrust coefficient (CT)
301	0	0.0	0.005873
302	-2	0.1	0.005876
303	-6	0.2	0.005905
304	-8	0.3	0.005930

4. RESULT

4.1. Data processing

Blade motion can be expressed as sum of harmonics of revolution. Therefore spectral analysis technique is effective in signal processing of the raw data; which are the converted flap, lag and torsion deflections from the coordinates of the markers. Because the Nyquist frequency of the sampled time history is the half of the sampling frequency, the sampling frequency should be at least over 216Hz to obtain harmonic motions of up to 6th order. This high sampling frequency can be limited by equipment performance. However blade motion is periodic, and if we consider the data in azimuth axis, we can re-produce the data in azimuthal domain with increased resolution than time domain. Theoretically, the sampling frequency of 209 Hz provides the azimuthal resolution of 1 degree after 30-second measurement when the blade motion is assumed steady.

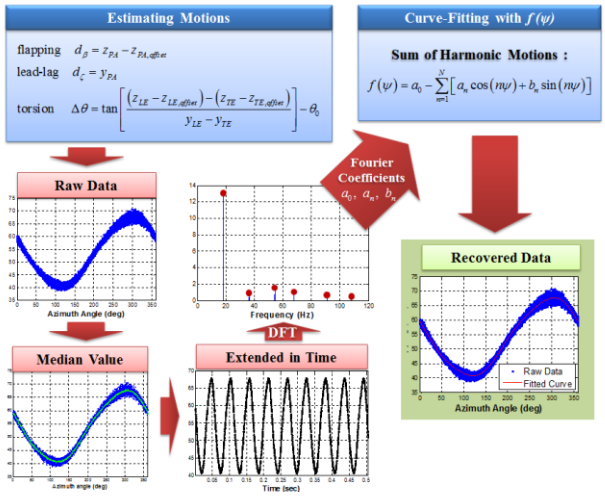


Figure 10 Data processing procedure

Figure 10 shows the procedure of the signal processing. First, raw data was rearranged with respect to azimuth angle, and then median values of the motions were calculated at every 1 degree step. This stage generates 360 data points per revolution; which can be considered as a data set with 6,480 Hz sampling rate in time domain. So we can extract harmonics up to 180/rev. But too much higher harmonics are not required in many cases and there was no such a high frequency harmonic responses in blade motion in this test result. Therefore harmonic solutions up to 6/rev were extracted and used as a fitted result to obtain the blade motions.

4.2. Blade pre-twist

Blade pre-twist angles are necessary for the calculation of elastic torsion. Figure 11 shows designed and measured pre-twist angles using SPR system at non-rotating condition.

There are some differences between designed and measured values; differences of painting thickness, error of marker locations, and measurement uncertainties are considered to be the cause of these discrepancies.

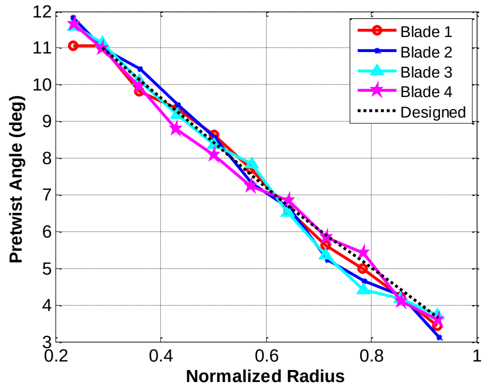
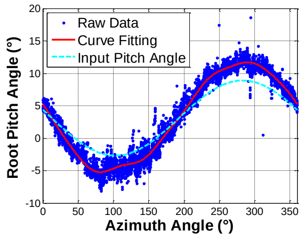
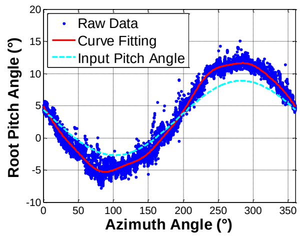


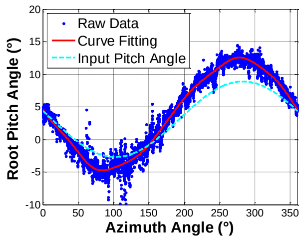
Figure 11 Pre-twist angles



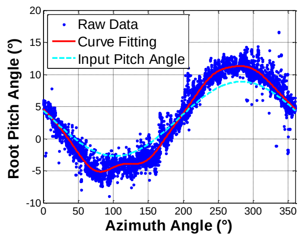
(a) Blade 1



(b) Blade 2



(c) Blade 3



(d) Blade 4

Figure 12 Pitch angles for test 304

4.3. Pitch control angle

As described in section 3.1, blade pitch angles were extracted using the markers on the sleeves and pitch horns. Measured pitch angles for test no. 304 are compared with pitch control command in Figure 12. Collective angles look similar, but measured cyclic pitch angle is higher than control input. The measured pitch angles by SPR should be compared with other pitch angle sensors, but the installed pitch angle sensors did not work properly. Pitch angle measurement should be investigated more in the future test.

4.4. Flapping

Raw data of flapping deflections of the blade 1 at r/R=0.929, 0.645, 0.431, 0.238, and fitted data at r/R=0.929 for test no. 304 are given in Figure 13. Maximum flap deflection occurred around azimuth angle 330 degree and minimum flap accurred around 170 degree. So the tip path plane tilted forward about 2.3 degree.

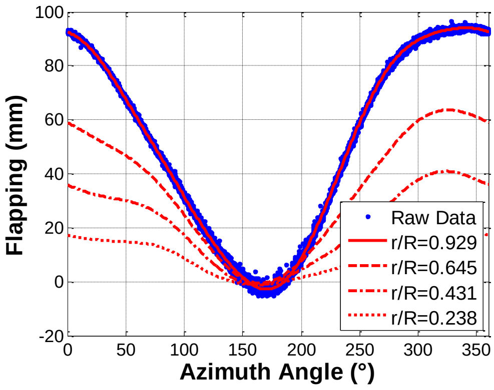


Figure 13 Flap deflection (blade 1, test 304)

Radial deformation shape of the blade 1 at azimuth 0, 90 and 180 degree is shown in Fig. 14.

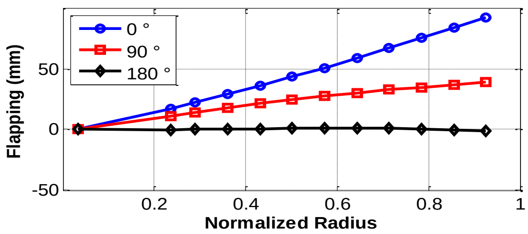


Figure 14 Flap vs. radius (blade 1, test 304)

4.5. Lead-lag

Lead lag deflection shows more scattering than flap deflection. Figure 15 shows lead-lag deflection of blade 1 at the same condition of Figure 13. In spite of more scattering than flap motion, it was not difficult to obtain lead-lag deflection through data processing.

4.6. Torsion

Elastic torsion is relatively small compared to flap and lead-lag and the scattering of the data is much high. So the fitted curve may have more error than flap and lead-lag. Figure 16 shows torsion deflection of blade 1 at the same condition of Figure 13 and 15. In order to identify torsion deflection in radial direction, pre-computed mode shapes of first two torsion modes were utilized as the similar manner in the reference [7]. The surface fitted torsion deflection for test no. 304 is given in Figure 17.

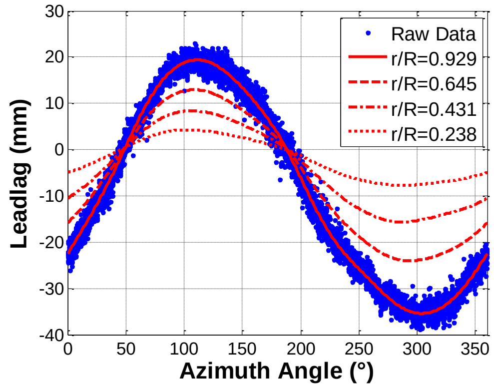


Figure 15 Lead-lag deflection (blade 1, test 304)

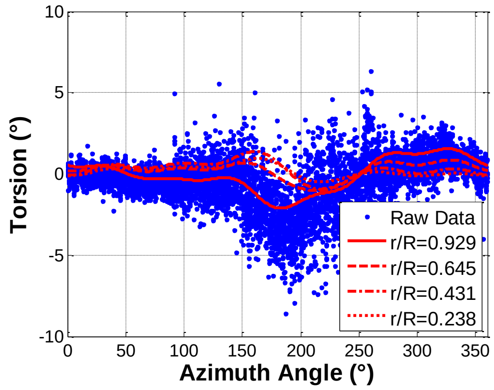


Figure 16 Torsion deflection (blade 1, test 304)

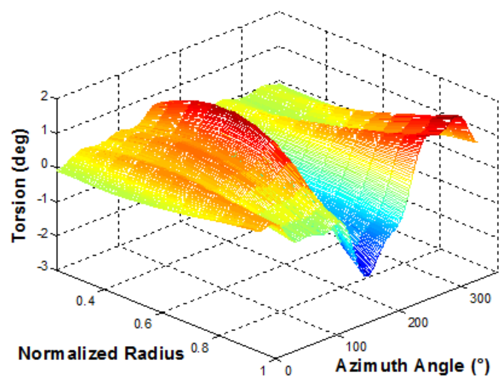


Figure 17 Torsion motion (blade 1, test 304)

4.7. Standard deviation of measurement

The measured data have a scattering from the reconstructed fitted curve. Table 5 is the summary of the standard deviations for four test conditions. These are averaged values for all four blades. The mean std. value for flapping is 0.41 mm, lead-lag is 0.72 mm, and torsion is 0.48 degree. For flap and lead-lag motions, these values are relatively small compared to maximum deflection. However the torsion has relatively high standard deviations compared to its peak-to-peak values. So it is required to increase the accuracy for measuring torsional deflection.

Table 5 Averaged standard deviation

Test No.	Flap (mm)	Lead-lag (mm)	Torsion (deg.)
301	0.41	0.58	0.44
302	0.28	0.61	0.39
303	0.44	0.80	0.47
304	0.50	0.87	0.63
Avg.	0.41	0.72	0.48

5. CONCLUSION

An SPR system with IR cameras was applied to the blade deformation measurement. Continuous data acquisition without synchronization to a specific azimuth angle was successfully demonstrated. For the data processing, acquired data points could be rearranged with respect to the azimuth angle, and then harmonic solutions were estimated. From the result of test, it was found that the averaged standard deviations for flap, lead-lag and torsional deflection are 0.41 mm, 0.72 mm and 0.48 degree respectively. Flap and lead-lag signals look clear compared to torsional deflection.

The SPR system applied to this study showed advantages of using IR cameras in relatively bright condition and continuous data acquisition without synchronization with azimuth angle. However present system was not sufficiently verified at high speed rotating condition. And it is also necessary to increase the accuracy for measuring the torsional deflection.

ACKNOWLEDGEMENT

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