CONSIDERATIONS IN BUILDING AN SPR SYSTEM FOR ROTOR BLADE DEFORMATION MEASUREMENT

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Abstract

A blade deformation measurement system utilizing Stereo Pattern Recognition (SPR) technique has been designed and built. Components of the system were selected considering the size of the model rotor and target accuracy. When considering the 4 m by 3 m measurement area in order to measure the deformation of the 2.5 m diameter rotor blades, the system was designed to have a resolution of the 3D deformation data in the range of 0.1 mm. The azimuthal position of the rotor should be controlled as exactly as 0.01 degree by a time delay control of the trigger signal. The combination of Xenon stroboscope lamps with LEE 799 UV filters, cameras with Edmund 575 nm filters, and rotor blade markers painted with orange/yellow fluorescent paint provided excellent contrast. Image processing and analysis, 3D tracking and reconstruction, and measurement automation functions were validated through initial tests.

1. INTRODUCTION

The deformation of the rotating rotor blades is important information for predicting the aerodynamic performance as well as the structural characteristics of the helicopter rotor system. Accurate blade deformation data are necessary for improving analysis results. Different methods of extracting deformation information of the blades in high speed rotating environment from acquired images have been applied in the past. The Fringe Correction Method (FCM) [1], which has been used in HART I (Higher-Harmonic Control Aeroacoustic Rotor Test I) and ATIC (Advanced Technology Institute of Commuter Helicopter) tests, is based on the projections of a stripe pattern on the rotor blade surface at a specific azimuthal position and the processing of the acquired image from a different viewing angle. Out-of-plane deformation can be extracted at high resolution from the relative displacement of projected stripes on the surface. It has advantages of simple set-up of one camera and one projector, high resolution up to 1/20 of the pixel size, and the possibility of obtaining continuous data of the entire blade surface. However, there is a disadvantage that dirt or scratches on the surface affect the accuracy of the data. A similar method, Projection Moiré Interferometry (PMI) [2], is also based on the projection of a pattern and has some advantages concerning surface contamination, but it is theoretically known to have lower resolution than the FCM method. The Stereo Pattern Recognition (SPR) technique [3], has been successfully applied for the HART II test. It is based on the imaging of the position of clearly visible markers by means of two cameras in stereoscopic set-up. The SPR method can extract 3-dimensional coordinates and is free from disturbances by surface contamination or scratches. The resolution of the SPR system is better than 1/10-pixel within the 2D-images if the markers are not smaller than 10 pixels [3]. Higher resolution of 1/10 ~ 1/20 pixel can be achieved depending on the maker size, contrast, and other parameters. The signal processing time is much shorter than FCM and real time measurement is also possible. Other methods include a commercial system for motion capture (Eagle Digital RealTime System, Motion Analysis) which has been applied in an attempt for blade deformation measurement [4]. It has advantage of continuous measurement by using high speed cameras, but the measurement performance at high speed rotating condition was not acceptable. To overcome the difficulties in using the motion capture equipment for the blade deformation measurement, the authors proceeded to design an SPR system which has similar mechanism as used in the HART II test. Triggered measurement technique instead of continuous measurement was applied for stable and reliable data collection even at high speed rotation. This paper introduces the process of selection of components of the new system and considerations in optimizing an SPR system that

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

can be used for reliable and accurate rotating blade deformation measurement.

2. SYSTEM CONFIGURATION

The SPR system consists of many components. The schematic diagram of the SPR system is shown in Figure 1. For the first tests and validation of all components, the system is installed in a hover test stand.

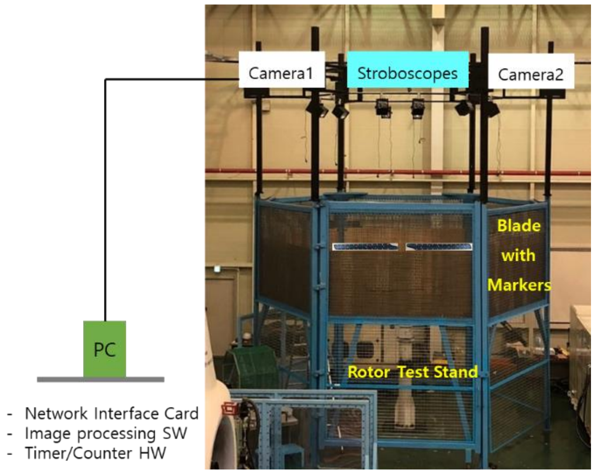


Fig. 1 Configuration of the SPR system

2.1. Rotor test stand

The rotor test stand should have all necessary hardware and software to run the rotor and to produce a trigger signal once per revolution. The trigger signal is a normal TTL signal and fed into conditioning equipment to generate trigger signals for cameras and strobes with same timing. It is very important that this trigger signal has no or very little jitter. At the design tip speed of 220 m/s of the rotor, a jitter of 1 microsecond would already result in an azimuthal error of 0.01 degree.

2.2. Rotor blades with markers

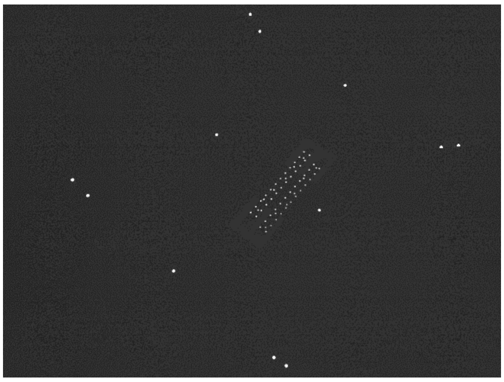
Rotor blades with markers with fluorescent paint are necessary to guarantee highest possible contrast. The positions of measurement markers are close to leading edge and trailing edge to identify blade deformation in flap, lag and torsion. To enable the software to detect and match all markers in the stereoscopic images automatically, another set of randomly positioned markers has to be provided. This helps to distinguish each blade and each radial position of each blade.

Fig. 2 Rotor blade with measurement and random markers

2.3. Cameras and acquisition hardware

Two high resolution cameras EVT HR20000M from Emergent Vision Technologies with 5120 x 3840 pixels are arranged at a viewing angle of 50 ~ 70 degree. The camera has a CMOSIS CMV20000 sensor with 6.4 μm pixel size. Compared to other high resolution sensors, this sensor has amazingly low noise even at high gain factors. The camera is relatively fast with 30 fps and is connected to the computer via a 10 GigE interface with SFP+ modules and glass fiber cables.

(a) exposure time = 1000 μs



(b) exposure time = 2 μs

Fig. 3 Effect of exposure time

Exposure time is also an important parameter for acquiring high contrast images. However, it should be noted that the exposure time will mainly influence the brightness of the LED calibration markers (see Fig. 3). The brightness of the blade

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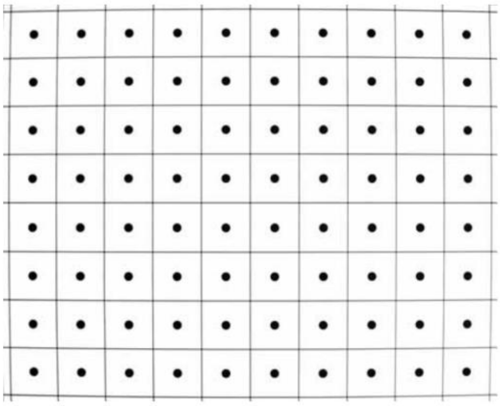
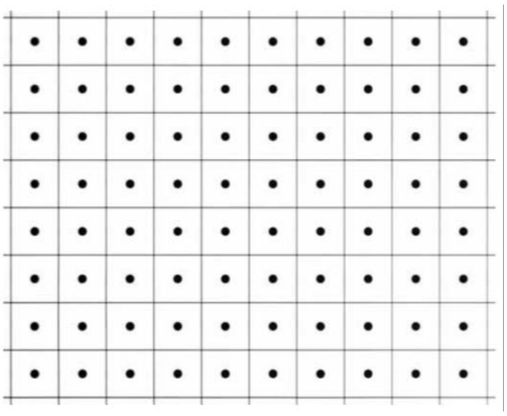
markers, however, are not really affected by the exposure time, only by the flash duration. Too long flash duration might result in motion blur at the high tip speed. For this problem it seems possible to cut short the flash duration by setting shorter exposure time than the flash duration.

2.4. Lenses, lens mount, lens calibration

Two Sigma 35 mm F1.4 DG HSM lenses have been selected considering the measurement area of 4 m x 3 m. The lenses are mounted on Birger EF-Mount adapters. Geometrical distortion of the lens can be corrected by software. To do this, test images with a grid or with dots on a grid have to be acquired. A successful lens correction requires to have these test images placed exactly perpendicular to the optical axis of the camera and lens system. To obtain as high accuracy as possible, coefficients up to the power of 6 of the radial distortion equations are determined. This lens correction can be applied in real time by the analysis software.



(a) original image with some barrel distortion



(b) corrected image

Fig. 4 Lens calibration images

Fig. 4 (a) is the original image with some barrel distortion, and Fig. 4 (b) is the corrected image. The lines look straight. The distortion of a lens depends on the working distance setting of the lens. Therefore, it is recommended to take the test image at the same working distance as the later measurement. Of course this is difficult for large measurement volumes. It is not easy to produce a test pattern of the size of the measurement volume, i.e. some 3000 mm in length. But it is a big advantage here that normally the lenses are wide angle lenses with a large depth of field. So even at half working distance the image will be not too much out of focus. Some small blur can be accepted. After all the measurement is based on the determination of the black circles and even if these circles are blurred their centers can be determined very exactly. Typical lens distortion for wide angle lenses can be up to 2 % of the image size. With these high resolution EVT cameras this can be up to 100 pixels of distortion at the image borders. After correction the errors should be as small as possible. Depending on the quality of the test images and on the mathematical distortion function of the lens it is possible to correct the distortion with a final error of 0.5 ~ 1.5 pixel. As soon as the lens distortion factors, the kappa values, are known, the acquisition of calibration body test images and rotor test images can start.

2.5. Bandpass filter

While it would be possible to perform measurements with normal high contrast markers, either black markers on white background or vice versa, light reflections on the curved blade surface would always result in bad contrast or reflections at certain regions of the blades. Also a perfect even illumination can normally not be provided. As a result, it might be difficult to find all markers on the blades automatically, especially if other marker-like spots can be detected in the background. It has been proven that using UV light for illumination and fluorescent paint results in perfect bright markers and very little background disturbances [5]. Additionally, when a narrow band filter for the exact frequencies of the emitted light of the fluorescent paint (530 nm or 575 nm) is used, everything but the markers will disappear in the black. Automatic marker search with global gray level threshold is possible. These filters can be placed in front of the lens, but this arrangement has two disadvantages: large narrow band filters are expensive, and for wide angle lenses the filters will have bad side effects at the outer border, like frequency shift or other. Therefore, the filters are optimally placed in the lens adapter between lens and camera sensor. The lenses are adapted with Birger EF-mounts to

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the cameras M58 lens mount thread which provide enough room to insert the filters.

To get high contrast and high brightness images, combinations of two different bandpass filters for lens (MidOpt 525 nm, Edmund 575 nm), two filter foils for Xenon strobes (LEE 181, LEE 799), and two colours of fluorescent paint (yellow/green, orange/yellow) have been examined. It was found that the combination of Edmund 575 nm filer, LEE 799 filter, and orange/yellow fluorescent paint showed high contrast and brightness image at an F-stop of 4.0 as shown in Fig. 5. The combination of Edmund 575 nm filter and LEE 799 filter showed more or less the same brightness and allowed even to close the lens down to F-stop of 5.6. Due to the fact that the Edmund filter has a better IR-blocking and therefore does not require an extra IR filter, this combination was selected.

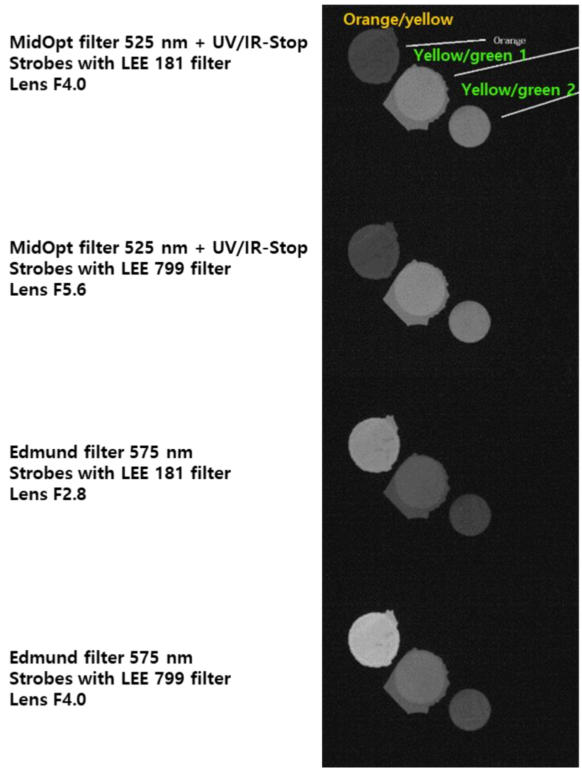

Fig. 5 Test images with different filters and paint colours

2.6. Analog Xenon strobes with UV filters

Xenon strobes have a very high UV part in their light emission. Ten 50 W SuperStrobe MKII strobes have been arranged to illuminate the measurement volume. These strobes have been provided by courtesy of the DNW (German Dutch Windtunnel). These strobes have strong flashes of relatively short duration of only several microseconds and can be triggered with signals of 8 ~ 15 Volts at frequencies of up to 15 Hz. It is important to use “old fashioned” analog controlled strobes to get an exact trigger to flash timing. “Modern” digital strobes, normally with USB control interface, cannot be triggered that exactly. Additionally, large sheets of filter foil (LEE 181 or 799) are placed on the front glass of the strobe devices to block everything but the UV and dark blue light.

2.7. Cameras and strobes mounting frame

A very stiff frame to hold two cameras was designed. It is necessary to maintain the position of the cameras relatively to each other and to the rotor very exactly during the complete measurement. The strobes are also attached to this frame.

2.8. Calibration frame

To be able to perform a 3D-measurement, the measurement system has to be calibrated. A calibration frame was constructed for the calibration of the 3D measurement volume as shown in Fig. 6. This calibration frame has twelve illuminated easily distinguishable calibration markers. The position of calibration markers is known and they define the measurement coordinate system.

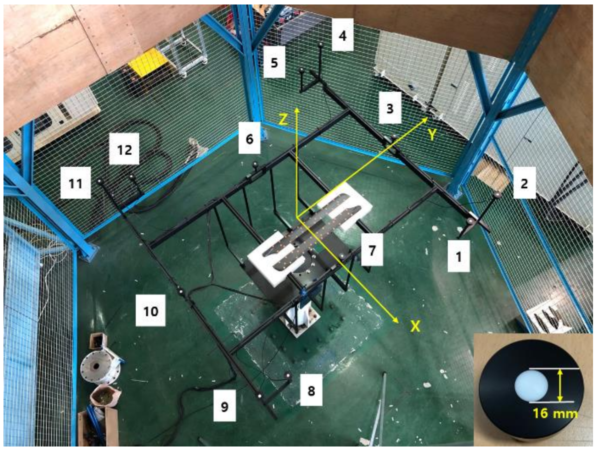

Fig. 6 Calibration frame with 12 markers

2.9. PC with acquisition and timer/counter hardware

A fast Windows computer including acquisition cards for the images, and a timer/counter card to produce conditioned trigger signals and delay times to control azimuthal position is required for

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the measurement. A National Instruments PCIe 6320X card was selected for the conditioning and delay control of the trigger signal. The resolution of the delay control is 1 μs, which makes the azimuthal position control possible with 0.01 degree resolution for a 2.5 m diameter rotor with tip Mach speed 0.6. A Myricom 10 GigE adapter is ready to be connected to 2 Emergent cameras. 64 GB of computer memory help to acquire long image sequences and fast SSD storage allows to save these image sequences for later post-processing.

2.10. picCOLOR software

The picCOLOR software (FIBUS Research Institute) has many functions including camera control, trigger conditioning and delay, image acquisition, post-processing and analysis functions. A special MACRO (script) interpreter allows to set up the complete environment before the start of the measurement and also allows to do automatic or half automatic measurement and/or post-processing. Most important functionality of the picCOLOR software are the many different 3D methods, like the SPR used for the measurement described here, the Fringe Correlation Technique, and different Interferometry methods, and also the flexibility to use many different brands of frame grabbers and cameras for high resolution and high speed acquisition.

3. BLADE MEASUREMENT

The measurement of the rotating blades and their deflections or deformations is performed by a 3-dimensional reconstruction of 2-dimensional marker locations in short exposure camera images. For the 3-dimensional reconstruction, either the exact positions of the cameras and characteristics of the lenses have to be known, or, as this is hardly ever possible, the exact location of several markers within the measurement volume. This is the so-called calibration marker set as explained before. Once at least 6 markers are known with their x-, y-, z-coordinates within the desired coordinate system, the reconstruction equations can be solved [6, 7]. If more than 6 markers are available, the Gauss-method can be used and provides even higher accuracy and also error vectors during calibration.

This stereometric method requires at least two cameras, arranged and adjusted to see all markers at all times. If more than two cameras are available, data redundancy provides much more data safety and the method allows to track even markers that are invisible in some of the camera views. However, to set up a system with more than two cameras is extremely complex. When the number of markers, i.e. of measurement positions on the rotor blades, is not too high, then a simpler system with only two cameras should be sufficient. To verify this fact is one of the side-goals of this measurement.

3.1. Image acquisition

Image streams from the two cameras are acquired via the 10GigE network card and stored directly into the computer memory, into two large ring buffers, one for each camera. Each image has its own time stamp. This allows to check for consecutiveness of all images and helps to debug the system in case of hardware or software errors.

Fig. 7 Blade markers with UV illumination

The images in the ring buffers can directly be analysed in real time during acquisition, if the analysis time is no longer than the frame time, i.e. 33 ms at 30 fps for the maximum speed of the available cameras. In this case, a measurement can practically last for ever. This is possible for simple non-rotating 3D-tracking cases, even with many markers, like aircraft wings. For a rotor test, however, where tip speed is extremely fast and the azimuthal position of the blades is controlled by several hardware events like hardware trigger from the rotor, delay settings, and stroboscope flash timings, it cannot always be guaranteed that markers move smoothly from frame to frame and can be tracked safely. For this type of measurements, markers could be lost during consecutive real time tracking. To avoid this problem, a special technique is used, tracking markers not consecutively from one image to the following image, but to analyse each stereo image pair as confined measurement position, using the Fundamental Matrix and Epipolar Geometry. As this costs much more computer time than simple tracking, therefore a post-processing of the images is recommended where marker-search-parameters can be optimized before-hand to find all markers safely. Another reason for the post-processing can be a tremendous amount of markers on the rotor blades (tests have been performed with up to 250 markers). All this cannot be analysed anymore

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within 33 ms. Therefore, the images are saved to hard disk directly after the acquisition. Most simple procedure would be to fill up the two ring buffers completely, then stop the acquisition and save the images. After this, a new acquisition can start. This procedure provides relatively long measurement times of 25 seconds with two cameras running at 30 fps and usage of 30 GB of computer memory for the ring buffers (Two 20 MPixel cameras at 30 fps at 8 Bit per Pixel amounts to 1.2 GB/s).

If the computer has very fast hard disks, like RAID arrays of SSD disks or even PCIe-SSD disks, then a special mode of the picCOLOR software can be used to save the images in real time during acquisition. Even if the hard disks cannot manage the data rate of 1.2 GB/s completely, the acquisition time can be much longer than those 25 seconds explained above because it can take some time before the acquisition pointer in the ring buffer crashes into the not yet saved images. If the write speed of the disk system is, for instance, only half the required speed, the measurement can be almost two times as long.

For the delayed trigger mode to set every requested azimuthal position of the rotor, images are not taken for every rotor revolution, but only every other rotor turn or even less. This will decrease the acquisition speed and therefore the measurement time will be long enough for most types of measurements.

3.2. Image analysis

As explained above a real time tracking cannot be recommended due to the risk of losing markers due to trigger uncertainties or other difficulties. All images will be available on hard disk for later processing and in case of problems all analysis parameters and even calibration parameters can be optimized to provide perfect data sets. Due to the perfect visibility of all UV-illuminated markers on the rotor blades with high contrast and sharp borders, all markers in both stereo images can be found with a relatively simple global gray level threshold. During the further steps of the analysis, optimized gray level thresholds are calculated to provide high accuracy 2D marker center coordinates. Using sub-pixel algorithms, this can be exact to some 1/10 ~ 1/20 pixel, which translates to some 0.1 ~ 0.05 mm 2D resolution with the actual size of the measurement volume and the 20 MPixel cameras. Reconstruction from 2D to 3D will introduce some rounding errors and some uncertainty due to the angle between the two cameras, resulting in a 3D-resolution of some 0.2 ~ 0.1 mm. These are local accuracies which can be used to calculate distances between close markers, or for instance to measure angles of attack of the rotor blades at high accuracy. It is necessary to distinguish this from the global accuracy, for instance for the measurement of the rotor diameter. For this global accuracy, it has to be taken into account that lens distortions can never be corrected fully; there will always be some lens distortion error of up to 0.5 or 1 pixel, which translates to a global (over the complete measurement volume) accuracy of no better than 1 ~ 2 mm.

The found markers are numbered from 1 to N1 and 1 to N2 in the two stereo images. Of course this numbering can be different in the two images due to the different view of the two cameras, and also due to the possibility that some markers might turn out as not found, or spots in the background are mis-interpreted as markers. This may happen even if so-called "rejection criteria" are being used by the analysis software. Most useful criteria are size and roundness. But of course these criteria cannot be set too distinguished because markers can change their size and shape while the rotor is rotating and the angle and distance from the cameras is changing. For a 3D-tracking, the software now has to find matches of the markers in the two stereo images. This is being done by applying Epipolar Geometry. With a calibrated system and known Fundamental Matrix for the two cameras in stereo setup, a single marker in one image translates to an Epipolar line in the other image. Solving all these conditions, the software can now determine all marker matches within the two images. Disturbances, like bright spots in the background, will not have any match in the other image and will therefore be removed, resulting in a good data set with hopefully all markers. Of course it is still possible that one or more markers are missing from the data set.

Next step now is the task to put all randomly numbered markers into the required order, for example leading edge root to tip, and then trailing edge root to tip. This is being done by a "re-labelling" step, where all marker positions are compared to the markers in a pre-defined data set, like CAD data or a manually ordered data set. This "re-labelling" step can also extend the marker set in case one or more markers are missing. This "re-labelling" is based on the relative distance of all markers to their neighbours in 3D-space. This is the reason for the existence of the randomly distributed markers on the blades (see rotor blade image Fig. 2). If there were only perfectly regularly and symmetrically placed markers on the blades, the algorithm would not have any chance to distinguish the marker from their neighbours. With the random markers, each local neighbourhood will be different and the algorithm can always know all

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marker relations. Tests with the 60 markers on the two blades showed that this algorithm can do a save "re-labelling" when at least 90 % of the markers are determined correctly by the Epipolar Geometry step. Final result is a 3D-data set of the marker centers for each stereo image pair (Fig. 8).

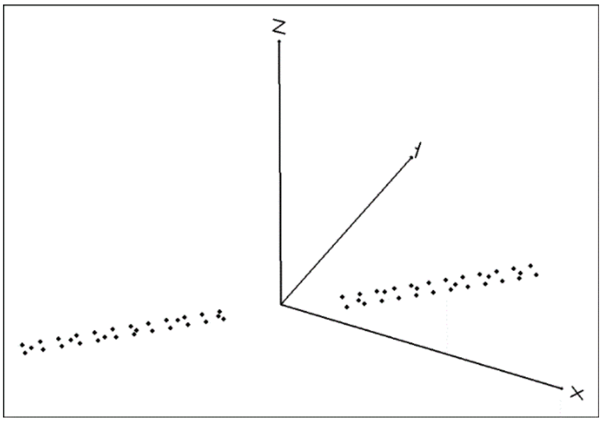

Fig. 8 3D marker coordinates after reconstruction and re-labelling at 45-degree azimuth position

Depending on the measurement mode, either a continuous rotation of the rotor or a set of selected azimuth positions of the blades can be measured. This latter measurement type will be the normal case. As there might be trigger and delay uncertainties and also statistical flow disturbances and turbulence, it makes sense to measure each rotor azimuth position for a longer time and do some statistical considerations with the data sets, like averaging, to get one final data set for a quasi-steady blade motion.

With these data sets, flapping and lead-lag motion of the blades can be determined, and also blade torsion. Of course the blade torsion and angle of attack values during rotation and especially during forward flight tests are important. It is desirable to get blade torsional data as accurately as possible. With the small chord size of the rotor blades, however, and the given accuracy of the marker tracking, the resolution of the angle of attack of the blades might not be good enough. Therefore, some simple polynomial curve fitting of the markers on leading and on trailing edge will be included. With these data, the accuracy can be improved a lot.

3.3. Measurement automation

While it is normally recommended to analyze one image manually and interactively to find the best parameters for analysis, thousands of images of longer measurement sequences cannot be analyzed this way. Therefore, special script programs, called "Macro"-programs, are designed and then interpreted by the picCOLOR software. Images on hard disk are identified by their root name with measurement point information, some abbreviation for left or right image, and a consecutive number. Those file names can be build up within the Macro program and then the Macro program can load the images and start analysis. After initializing the processing environment with all optimized parameters, the picCOLOR software will load one pair of stereo images after another into the computer memory and there all markers are searched, matched by Epipolar Geometry, "re-labeled" to match a given data set template, and then the 3D-data set is written to file or sent to another computer via TCP/IP. All further processing is then done with other programs.

4. SUMMARY

An SPR system has been designed and built considering the 4 m by 3 m measurement area in order to measure the deformation of the 2.5 m diameter rotor blades. Selection of the components for the new system and optimizing the SPR system were explored. The summary of this investigation is as follows:

1) Two high resolution cameras with 5120 x 3840 pixels were selected to provide a resolution of the 3D deformation data in the range of 0.1 mm considering the 4 m by 3 m measurement area and using sub-pixel algorithms.

2) The combination of Xenon strobes with LEE 799 UV filters, cameras with Edmund 575 nm bandpass filters, and the markers painted with orange/yellow fluorescent paint provided excellent contrast.

3) Typical lens distortion for wide angle lenses can be up to 2 % of the image size, which can be up to 100 pixels of distortion at the image borders. It is possible to correct the distortion with a residual error of 0.5 ~ 1.5 pixel.

4) A calibration frame was constructed for the 3D measurement volume. Twelve reference markers were used to calibrate a 2000 mm x 1800 mm x 280 mm volume. The calibration markers could be manufactured and measured with an accuracy of 0.5 ~ 1 mm. With these, the 3D coordinate system was defined and calibrated with less than 1 mm global error.

5) The trigger signal from the rotor can be conditioned to control the stroboscope and the camera exposure at all desired azimuth positions with an accuracy of 0.1 degree.

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6) Test images of the rotor blades mounted to the rotor hub were taken at different azimuthal positions and were analysed by the picCOLOR software. Epipolar geometry was able to find between 90 % and 100 % of the markers and do the reconstruction of the 3D-data. Data sets were re-labelled to have the data in the required order, root to tip, leading edge and trailing edge. The re-labelling process could even reconstruct any missing marker.

7) Next step will be the acquisition and analysis of images at high tip speed.

5. ACKNOWLEDGEMENT

This study has been supported by the project ‘Study on the Core Technologies of Electric Vertical Take-Off and Landing Aircraft’ funded by the National Research Council of Science and Technology. The authors would like to express their gratitude to all people making this investigation possible, especially to Mr. Gerrit Feenstra from DNW for providing the 10 stroboscopes for the illumination of the measurement volume.

6. REFERENCES

[1] Mueller, R. H. G., Pengel, K., “Fringe Correlation Method for Helicopter Rotor Blade Deflection Measurement,” 24th European Rotorcraft Forum, Marseilles, France, Sep. 15-17, 1998.

[2] Fleming, G. A., Gorton, S. A., “Measurement of rotorcraft blade deformation using Projection Moire Interferometry,” Shock and Vibration, Vol. 7, 2000, pp. 149-165.

[3] Pengel, K., Mueller, R. H. G., and van der Wall, B. G., “Stereo Pattern Recognition – the technique for reliable rotor blade deformation and twist measurement, ” Heli Japan 2002, AHS International Meeting on Advanced Rotorcraft Technology and Life Saving Activities, Tochigi, Utsunomiya, Japan, Nov. 11-12, 2002.

[4] Kim, D.-H., Kim, S.-H., Park, J.-W., and Han, J.-H., “Blade Deformation Measurement of a Model-Scale Rotor System Using A SPR System with IR Cameras,” 39th European Rotorcraft Forum, Moscow, Russia, 3-6 September 2013.

[5] Bartels, R., Kufmann, P., van der Wall, B. G., Schneider, O., Holthausen, H., Gomes, J., and Postma, J., “Testing Active Rotor Control Applications Using DLR’s Multiple Swashplate Control System in the LLF of DNW,” 42nd European Rotorcraft Forum, Lille, France, 5-8 September 2016.

[6] David F. Rogers, J. Alan Adams, Mathematical Elements for Computer Graphics, McGraw-Hill Book Company, 1976.

[7] David F. Rogers, “Quantitative Information from Helium Bubble Flow Visualization Using Computer Graphics Techniques,” AIAA 14th Aerospace Sciences Meeting, Washington D.C., January 26-28, 1976, also AIAA Paper No. 76-93.