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Blade Deflection Measurement at the Low Noise ERATO Rotor

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The ERATO rotor is a bilateral project by ONERA and DLR with the ambitious goal to design and test a low noise model rotor and perform comparisons with a reference rotor of current technology, the 7AD ONERA-EC rotor. A very important part of this project was the aeromechanic investigation of aeroelastic blade deflections, especially torsional and flapwise deflections. Two different measurement techniques have been used, the conventional strain gauge technique and the non-intrusive optical fringe correlation method (FCM), also known as projected grid method (PGM). This paper describes the principles of both methods and presents results and their comparison for different flight conditions, a descent flight at -6^o flight path and low and medium speed level flight. Overall agreement of the data of both methods is very good and differences are explained.

1 Introduction

During the bilateral ERATO project a low noise model rotor was designed by ONERA and DLR [1]. This rotor has been tested in different wind tunnels at various flight conditions and results have been compared with a reference rotor of current technology, the 7AD ONERA-EC rotor. For the understanding of the influences on aerodynamics and acoustics it is very important to have data bases of the aeroelastic blade deflections. This becomes especially important for the low noise ERATO blade with its innovative shape with swept forward and backward sections and its complex stiffness and momentum distribution. The deflection data like flapwise bending and torsion can also be used for verification of the numerical prediction codes. Therefore an extensive aeromechanic data acquisition programme has been performed besides of the acoustic and aerodynamic investigation. Two different techniques have been applied to provide the deflection data, the conventional strain gauge method and the non-intrusive optical fringe correlation method (FCM), also known as projected grid method (PGM). While some strain gauge results can already be found in [2], this paper will concentrate on the description of the two methods and on the comparison of the results. While overall comparisons of the results of both methods are in good agreement, it will be shown that both methods have their disadvantages and draw-backs, leaving a broad field of new developments and enhancements for the future. The strain gauge technique may have difficulties to resolve the complex deflections at the ERATO blade due to a certain degree of sensor coupling within the blade, the FCM may produce larger errors at the backward swept blade part and has an additionally increased uncertainty at the small chord sizes near the tip.

2 The Strain Gauge Method

Elastic blade deflections (relative to the rigid blade motion measured via the potentiometers at the hinge) are computed using the measured bending moment distribution and applying elementary beam bending theory. The stiffness distribution in flap (z, β), lead-lag (y, ζ), and torsion (ϑ), was provided by ONERA. From the entire set of strain gauges, 20 could be used for analysis of the 7AD rotor (8 in flap, 6 in lead-lag and 6 in torsion), and 23 in case of the ERATO rotor (10/4/9). Defect sensor signals were replaced by the data from sensors located at the same position on other blades, where possible. Based on elementary beam bending theory, the second derivative of the flap or lead-lag displacement at any station r is proportional to the ratio of the bending moment M and the local stiffness in bending, EI, or torsion, GJ.

$$\begin{Bmatrix} z'' \\ y'' \\ \vartheta' \end{Bmatrix}_r = \begin{Bmatrix} M_\beta/EI_\beta \\ M_\zeta/EI_\zeta \\ M_\vartheta/GJ_\vartheta \end{Bmatrix}_r$$

For calculation of the deflection, the blade was discretized into segments with constant EI or GJ, following the given distribution of these. A further assumption is that the moments vary linearly between consecutive measurement locations. Additionally, boundary conditions must be applied at both ends of the rotor blade. At the tip (free end) the bending moment must vanish and at the root (hinge) the deflection is zero in all degrees of freedom (but may be replaced by the measured flap, lead-lag and pitch angle at the hinge) and the slope relative to the measured flap and lead-lag angle is zero.

$$\begin{Bmatrix} M_\beta \\ M_\zeta \\ M_\vartheta \end{Bmatrix}_R = \begin{Bmatrix} z' \\ y' \\ \vartheta \end{Bmatrix}_{r_0} = \begin{Bmatrix} z \\ y \\ 0 \end{Bmatrix}_{r_0} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

Although it is an articulated rotor hub with coninciding flap and lead-lag hinge, the moments at the hinge are nonzero due to the presence of a lag damper, friction in the hinge etc. The root moments are not measured and therefore they are extrapolated from the first three strain gauges in radial direction. This may be subject to errors, but it will not affect the total deflection too much since the stiffnesses at the root are by orders of magnitude larger than at the airfoiled portion of the blade.

$$M_0 = M_1 + \frac{r_0 - r_1}{2}\left[\frac{M_2 - M_1}{r_2 - r_1} + \frac{M_3 - M_1}{r_3 - r_1}\right]$$

A first integration of the moments, starting from the hinge in radial direction, gives the slope in flap and lead-lag, and the elastic torsion. This is done for all positions r_j with $j = 0, \cdots, N$ with r_0 being the hinge location, $r_N = R$ the blade tip, and r_j the strain gauge locations. At $j = 0$ the boundary conditions are applied, and at $j = 1, \cdots, N$ the integration is performed:

$$\begin{Bmatrix} z' \\ y' \\ \vartheta \end{Bmatrix}_j = \begin{Bmatrix} z' \\ y' \\ \vartheta \end{Bmatrix}_{j-1} + \begin{Bmatrix} 1/EI_\beta \\ 1/EI_\zeta \\ 1/GJ \end{Bmatrix}_j \times \left[\begin{Bmatrix} M_\beta \\ M_\zeta \\ M_\vartheta \end{Bmatrix}_{j-1} (r_j - r_{j-1}) + \frac{\partial}{\partial r}\begin{Bmatrix} M_\beta \\ M_\zeta \\ M_\vartheta \end{Bmatrix}_j \frac{(r_j - r_{j-1})^2}{2}\right]$$

A second integration provides the elastic deflection in flap and lead-lag at $j = 1, \cdots, N$, with inclusion of the boundary conditions at $j = 0$.

$$\begin{Bmatrix} z \\ y \end{Bmatrix}_j = \begin{Bmatrix} z \\ y \end{Bmatrix}_{j-1} + \begin{Bmatrix} z' \\ y' \end{Bmatrix}_{j-1} (r_j - r_{j-1}) + \begin{Bmatrix} 1/EI_\beta \\ 1/EI_\zeta \end{Bmatrix}_j \left[\begin{Bmatrix} M_\beta \\ M_\zeta \end{Bmatrix}_{j-1} \frac{(r_j - r_{j-1})^2}{2} + \frac{\partial}{\partial r}\begin{Bmatrix} M_\beta \\ M_\zeta \end{Bmatrix}_j \frac{(r_j - r_{j-1})^3}{6}\right]$$

These integrations must be done for each azimuth, resulting in the elastic flap, lead-lag and torsion deflection as a function of radius and azimuth. They are deflections relative to the blade root motion at the hinge as a function of azimuth only. A rigid blade motion, based upon the measured angular deflection at the hinge, may be added in order to obtain total blade deflections. It must be noted that this strain gauge technique is generally limited in accuracy on one hand by the sensor data, i.e. their calibration, and on the other hand by the degree of coupling within the blade. Especially the ERATO rotor with for- and aft-swept portions places questions on the validity of this method.

Total blade deflections are then obtained by adding to the elastic deformation the rigid blade deflection due to the measured blade root flap angle, $(r - r_e)\beta$, with r_e being the radial blade hinge position. The flap angles are small since the trim was made to eliminate the 1/rev flapping. In pitch the total deflection can be obtained by adding the measured root pitch angle to the elastic torsion, plus the build-in twist distribution. However, in order to compare results directly with the FCM, the reference deflections have to be subtracted. These are obtained with the rotor in non-rotating condition and the blade positioned manually at the desired azimuth positions at almost zero flap angle and a given collective, but without cyclic control setting. Blade twist is thus eliminated since it is present in both the reference and the operational data set, and the same is in effect in the FCM results.

The accuracy of the strain gauge method described is difficult to judge. First, it depends on the given data set of stiffnesses, that usually are obtained from the design goal and not from local measurements of the real blade. Secondly, the accuracy of the flap and pitch potentiometers is limited to some $1/100^o$, where $1/100^o$ accounts for an error of $0.35mm$ at the blade tip of these rotors. Next, the strain gauges are calibrated in the nonrotating frame without centrifugal forces on the blade. Their influence on the strain gauges is unknown. Furthermore, the coupling of the moments due to the for- and aftswept

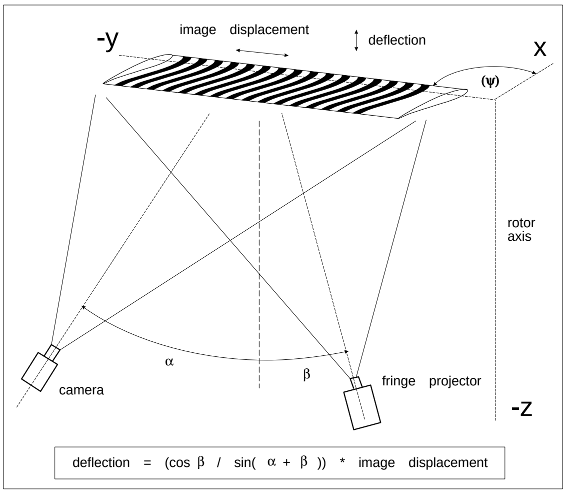

Figure 1: Principle of the FCM set-up

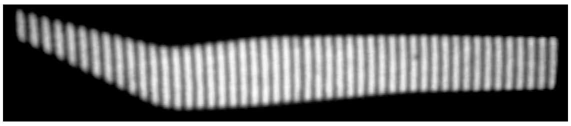

Figure 2: Example of the fringe pattern on the ERATO blade

portions is not yet introduced. Therefore, no accuracy bandwidth can be given for the strain gauge method. These uncertainties are the driving factor for more and more applying external methods in a complementary way, like the FCM described next.

3 The Fringe Correlation Method

The basic idea of the FCM is the detection of the displacement of projected patterns on the surface from a deformation or deflection of the surface using cross-correlation in frequency domain [3]. The projection of regular straight fringes perpendicular to the blade length as shown in Fig. 1 and Fig. 2 has the advantage of being almost not influenced by small blade lead-lag motion. This is very important as experience shows that it is not possible to set up the camera trigger at an absolutely exact blade azimuth position. This, however, is important when correlating the blade images with reference images at known positions. It could be shown that some small azimuth errors or some lead-lag motion or deformation of the blade does not have too much influence on the accuracy of the method.

Knowing the geometric arrangement with projector angle β and camera angle α relative to an axis of the defined coordinate system, for instance the windtunnel z-axis, the actual local

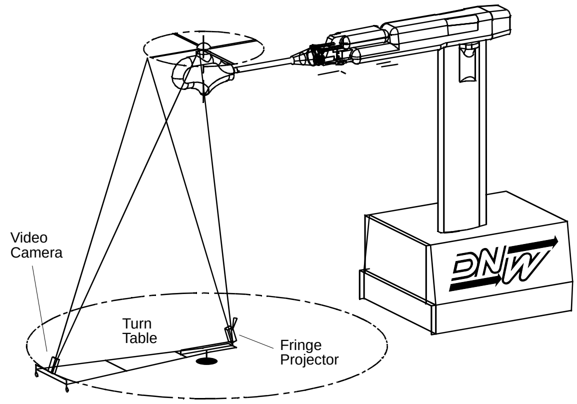

Figure 3: FCM set-up in the DNW

blade surface deflection can be reconstructed from the measured fringe displacement using a complex geometrical equation. For the special case of the intersection point of the optical axes of projector and camera the simplified equation in Fig. 1 applies.

For the ERATO measurement, a different set up for projector and camera from reference [3] was used to provide data close to the blade tip. Camera and projector have been exchanged to project the fringe pattern almost directly from below the rotor. The blade deflections now have almost the same direction as the fringe projection, resulting in small fringe displacements on the blade and no more lost fringes on the blade tip during strong vertical deflections, when compared to the former set up with the oblique projection.

Using this projector set up, the camera has to have an oblique view to the blade surface to produce large enough fringe displacements in the camera image to give the required spatial resolution. This set up results in some geometrical image distortions that can easily be corrected for data display after processing. One important advantage of the FCM when compared to other optical methods [5] is the possibility to reconstruct deflections using the original images that may be even heavily geometrically distorted without any correction procedure that would introduce rounding errors of similar order of magnitude as the correlation itself. Of course this applies for distortions from geometrical set up only - other distortions as optical lens distortions have to be taken into account in any case.

The turntable shown in Fig. 3 provides the possibility to measure at different azimuthal positions. For the ERATO test, only 5 positions at 30^o, 60^o, 90^o, 120^o, and 150^o azimuth have been used. Of course this is not enough to resolve higher harmonic flapping or torsional modes and recent investigations using the FCM have therefore always been performed at a higher azimuthal

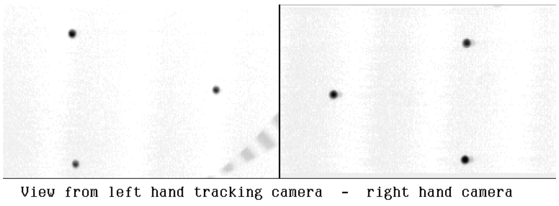

Figure 4: Stereo image of three marker LED's for 3D-tracking of rotor position

resolution, for instance at 15^o steps. Reference images have been taken at the non-rotating ERATO rotor, with known almost zero degree cone angle of the blades. For these images, the blade has been set to the required azimuth positions manually. All measurements or correlations are performed relative to this non-rotating reference positions with known flapping hinge angle and known cyclic or collective blade control setting. For the 7AD rotor, these non-rotating reference measurements are not available and therefore the reference images with the rotating rotor at zero thrust and no wind are used for reference. It is important to note that all FCM results are defined as relative data. When comparing to strain gauge data or numerical simulation results, the known flapping hinge angles and the known cyclic or collective pitch control input at the blade root for these reference conditions have to be subtracted to produce absolute data.

The correlation is performed using the two-pass technique already described in [3]. Additional test images have been acquired for different known rotor positions and blade deflections to check the accuracy of the method.

As the FCM is measuring deflections relative to the camera and projector positions which are set up and measured relative to the absolute windtunnel coordinate system, two additional position cameras in stereometric arrangement have been used to track the actual rotor position relative to the windtunnel system. Three LED markers (Fig. 4) on the model support have been tracked simultaneously with the FCM image acquisition and the motion of the model has been reconstructed. The measurements show a low frequency motion of a few millimeter amplitude. That motion has been subtracted from the FCM data. Tracking resolution is approximately $0.1mm$ and 0.1^o for yaw, pitch and roll motion. The angular tracking accuracy is not high enough to meet the resolution of the FCM at the tip, where a 0.1^o error would produce a flapwise deflection error of $3.66mm$ at the $2.1m$ blade radius. This difference has to be considered when comparing to the strain gauge measurements.

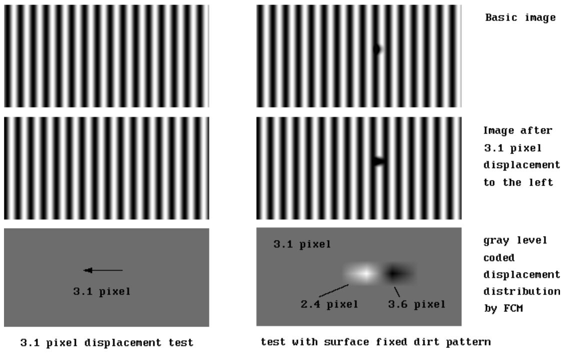

Figure 5: Examples of errors due to a blade fixed spot

4 Accuracy of the FCM

From cross-correlation in frequency domain the FCM can detect fringe displacements of as little a 1/20 picture element (pixel) in the digital camera image. A Proxitronic Nanocam intensified camera was used with the optics set up for a spatial resolution of $0.5pixel/mm$. Theoretically this would result in a displacement resolution of $0.1mm$. From the arrangement of camera and projector an additional geometrical translation factor applies, when the fringe displacement is converted to blade deflections. For the presented measurement this factor is in the range of $[1.8 \cdots 2.2]$, depending on the local position relative to projector and camera. Considering an average factor of 2 for this simple resolution estimation, the deflection resolution would be approximately $0.2mm$. Using single points at leading and trailing edge of the blade only and having a chord size of as small as $100mm$, the torsional resolution would be $\arctan[(0.2 + 0.2)/100] = 0.23^o$. One possibility to enhance this torsional resolution is a regression over many displacement vectors over the chord line which may increase the resolution by a factor of 3, resulting in a torsional resolution of better than 0.1^o.

All these considerations are valid for perfect clean surfaces only. Any tiny disturbance like dirt, finger prints from installation, or blade fixed structures will reduce the accuracy considerably due to the characteristics of the correlation. A simple test image may show this fact more clearly (Fig. 5): in the left hand side a mathematically exact sinus pattern has been used as a test pattern. The pattern has been shifted relative to the reference pattern by exactly $3.1pixel$ for example. The resulting vector field shows the $3.1pixel$ displacement result very accurately. Now a blade fixed pattern, a dark smoothly bordered spot has been introduced (see right hand side of Fig. 5) which is not moving during the $3.1pixel$ fringe displacement, i.e. during the simulated vertical surface

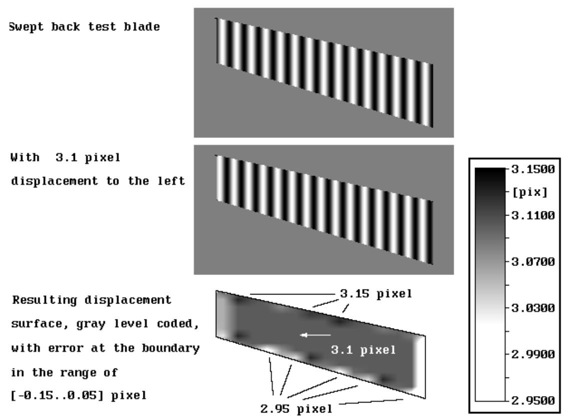

Figure 6: Examples of errors at leading and trailing edge due to correlation window characteristics

deflection. Now the resulting vector field shows large errors up to $0.5 pixel$ due to an interference of static and moving patterns in the disturbed region. This simple test shows the importance of absolute clean surfaces. Otherwise there may be a loss of accuracy by a factor of 5 to 10! For the torsion results, this would result in an uncertainty of $\pm 1^o$, too large for a useful measurement. Several of such error spots have been found on the test blades during data processing. To produce useful data, vectors in these regions have been replaced with the average of the neighboring displacement vectors.

Another problem encountered during the investigation is the complex ERATO blade shape itself: As explained in [3] and [4], the correlation is based on small rectangular windows covering several fringes in radial direction and only a few image lines, i.e. a few millimeters on the actual blade in chordsize direction to give the fine resolution in chordwise direction necessary for torsion determination. Typically these windows have a size of $32 * 5 pixel^2$. At the swept part of the tip, however, some of these windows may overlap the leading or trailing edge partly. Even using an artificial background gray level of the average gray value of the black and white fringe projection, some additional correlation errors arise from high frequencies introduced into the correlation spectra by the blade edges. These errors may be in the range of up to $0.2 pixel$, as shown in Fig. 6, again a simulation image with mathematically exact sinus patterns and a displacement of $3.1 pixel$.

This phenomenon is a draw back of the FCM and right now the only remedy is to neglect all vectors that are produced by edge overlapping correlation windows. This, however, reduces the usable chord size especially at the relatively narrow ERATO tip and results in a reduction of torsional resolution. Better procedures with oblique correlation windows will be designed and evaluated in the future. As a result of these considerations an accuracy of the FCM of better than $1mm$ in deflection and better than 0.3^o in torsion can be expected.

5 Results

Strain gauge measurements have been performed for all ERATO and 7AD reference rotor tests. The FCM investigation has only been performed in the low-speed-facility (LLF) of the DNW at descent flight condition and at low to medium speed forward flight. The tests discussed and compared in this paper are the descent flight at a flight path of $\varphi = -6^o$ at $V = 35m/s$, and low and moderate speed level flight at $V = 35m/s$ and $V = 60m/s$ respectively (see Fig. 7, Fig. 8, Fig. 9). Fig. 10, presents the out-of-plane deflections at descent flight for the ERATO blade, relative to a non-rotating, almost zero cone angle reference position in a gray level coded surface plot. Some deflection contour lines give an impression of the torsional blade angle, which is explicitely shown in the latter comparison figures.

Comparing the results of the two methods, the following observations can be discussed: For the 7AD reference rotor blade the comparison is excellent in any flight regime, especially for torsion. A few millimeter flapwise deflection difference at the tip can easily be explained by the possible model motion with 0.1^o to 0.2^o uncertainty in pitch or roll angle during the FCM measurement. Only the 150^o azimuth position shows larger differences.

For the ERATO rotor blade, there is also a good agreement in the flapwise motion. For torsion, the agreement is reasonable well at least for the larger part of the blade up to 75% of radius. Even the $4/rev$ torsional disturbance found in the strain gauge measurement can be observed in the sparse FCM data set with only 5 azimuthal positions. At the swept back part of the ERATO blade, however, larger differences occur. The FCM shows a considerable drop in torsion at the outer 20% radius that is obviously nonsense and that can only be explained by the additional errors due to small chord size and due to edge-overlapping correlation windows. Nevertheless the azimuthal development of the torsion data with the clearly visible 4/rev disturbance is similar to the strain gauge measurement up to the very tip. This fact implies the existence of some systematic error at either FCM or strain gauge technique and should be subject of future investigations. After all the complex shape of the ERATO blade may have some influence on the accuracy of the strain gauge technique due to

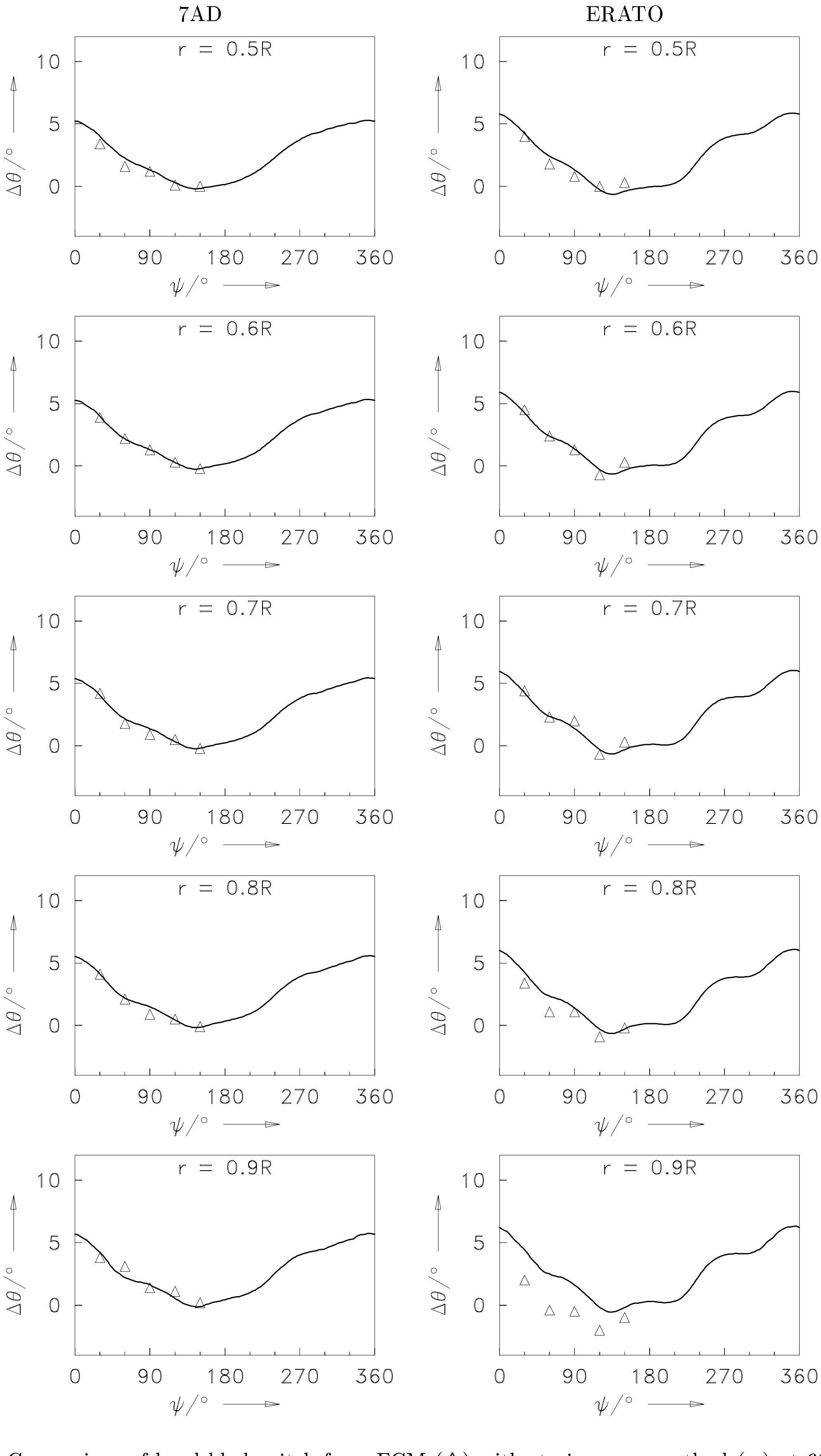

Figure 7: Comparison of local blade pitch from FCM (△) with strain gauge method (–) at 6^o descent, $V = 35m/s$

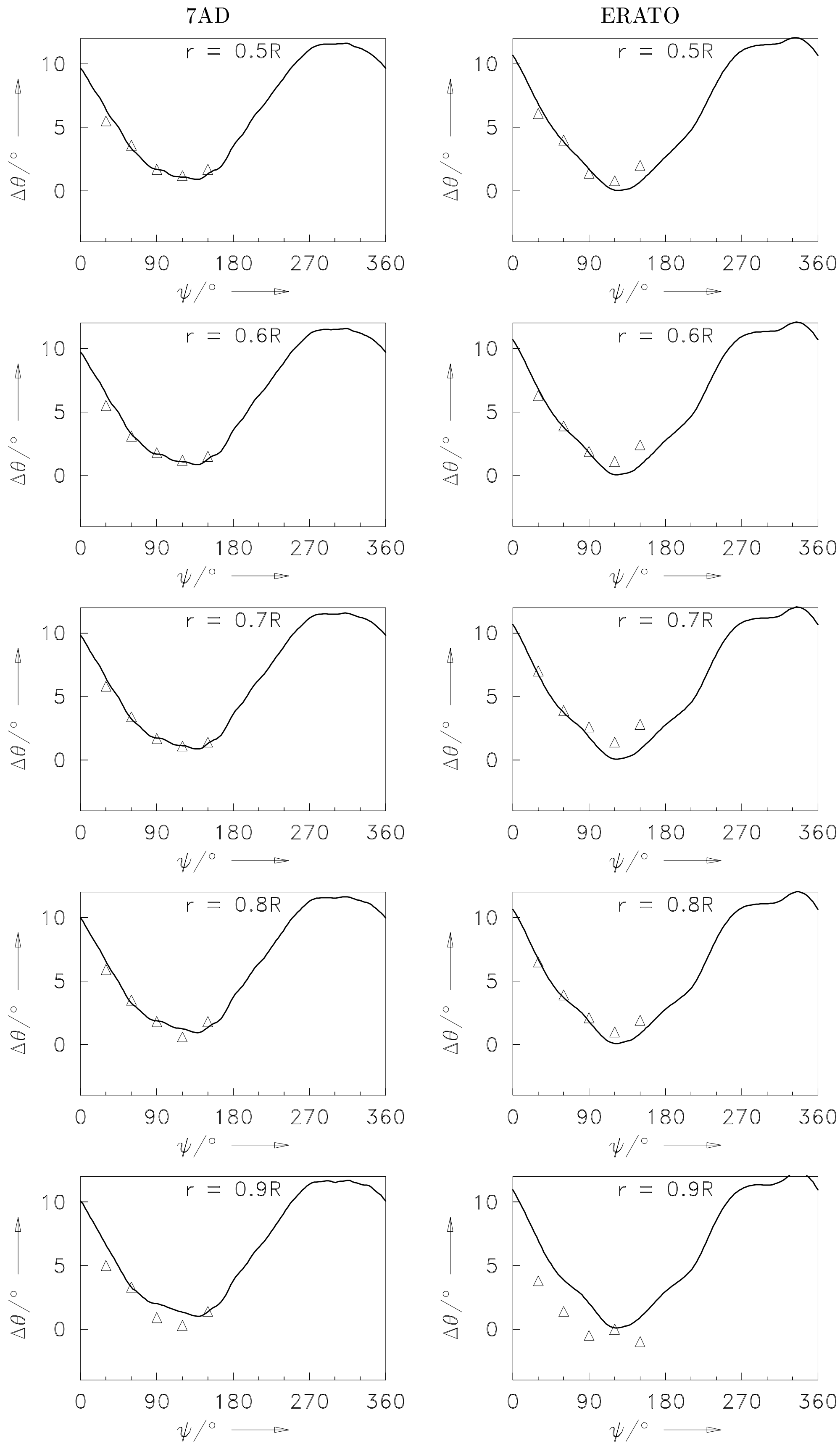

Figure 8: Comparison of local blade pitch from FCM (△) with strain gauge method (–) at level flight, $V = 60m/s$

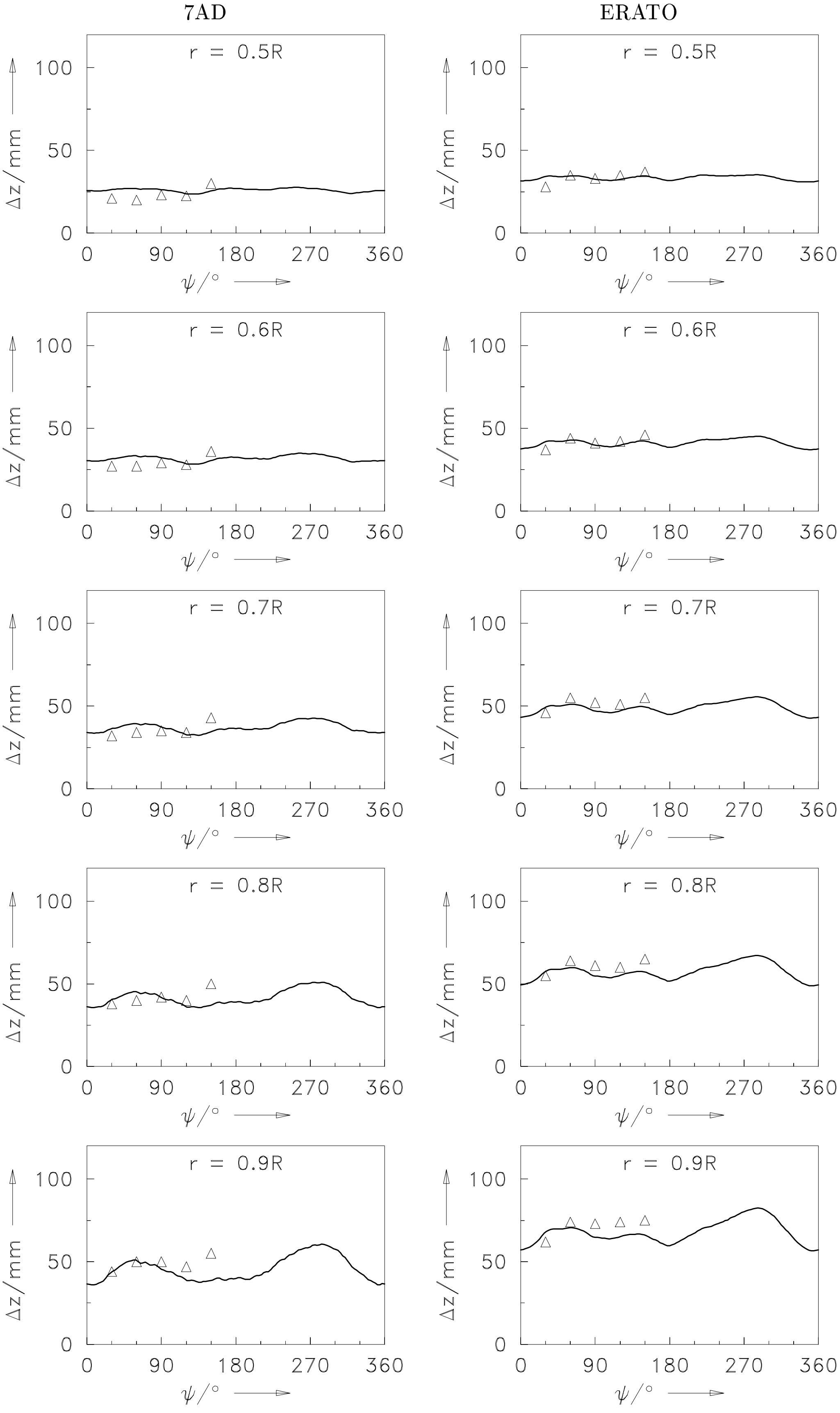

Figure 9: Comparison of local vertical blade deflection from FCM (△) with strain gauge method (−) at 6^o descent flight, $V = 35m/s$

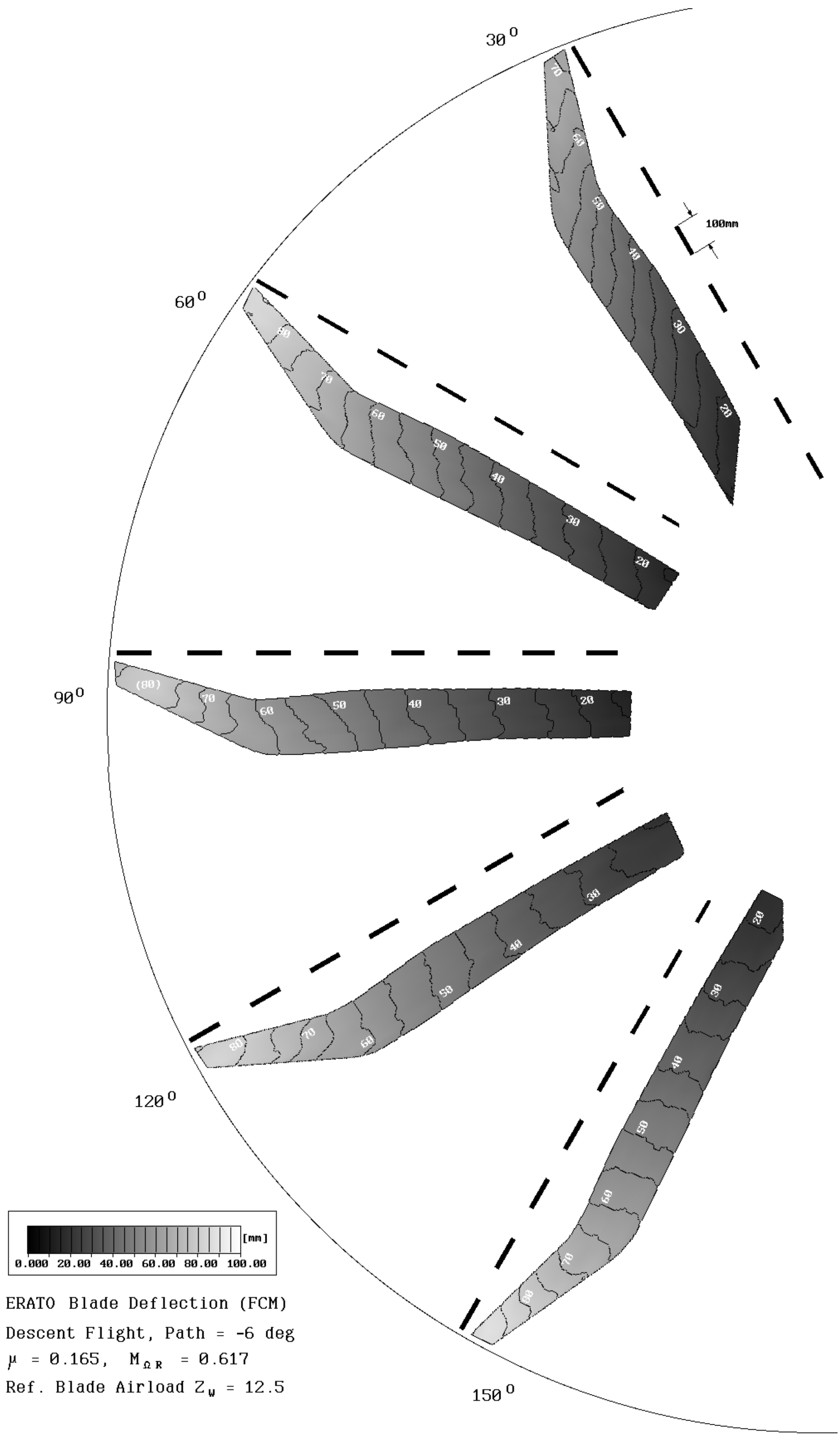

Figure 10: Out-of-plane deflections of the ERATO rotor at 6^o descent, $V = 35m/s$

coupling of flapping and torsion on the sensor output. Differences in the flapwise deflection between the two techniques can also be explained by the fact that two different blades have been used for FCM and strain gauge technique: the instrumented blade has too many surface fixed patterns to be used for the FCM measurement. Different stiffness and different flapwise and torsional modes of the blades can result in considerable deflection differences.

6 Conclusions

Two different methods have been used to examine the aeroelastic deflection and torsion of the blades of the aeroacoustically optimised ERATO rotor in comparison to the 7AD reference rotor. While the first method, the conventional strain gauge technique, requires a fully instrumented blade, the second method, the fringe correlation method (FCM) is a non-intrusive method that requires an optical fringe projector and a camera only. Specific patterns are projected on the blades and their displacement from blade deflection is measured using cross-correlation procedures at subpixel resolution. The resulting vector field of deflections over the complete blade surface can be used to determine flapwise deflection and blade torsion.

Comparison of the results of the two methods show a very good agreement for the 7AD reference rotor and for the largest part of the ERATO blade. There are considerable differences in the blade torsion only on the swept back tip of the ERATO blade that can be explained in different ways. Both methods have problems with the complex ERATO blade shape, the strain gauge technique due to the probable coupling of the sensor reactions, the FCM due to the - so far - unflexible correlation window size and the small tip chord size. Improvements seem possible and will be examined in the near future. In general, the FCM proved to be a faithful method that can be used with minimum set up requirements and no blade instrumentation.

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