ADVANCED METHODS FOR IN-FLIGHT FLAP GAP AND WING DEFORMATION MEASUREMENTS IN THE PROJECT AWIATOR

T. Kirmse, A. Wagner
DLR, Institute of Aerodynamics and Flow Technology
Bunsenstr. 10, 37073 Göttingen, Germany

OVERVIEW

For the investigation of the effectiveness of special high lift devices like mini trailing edge devices (Mini –TEDs) and sub-boundary vortex generators (SBVG) it is necessary to obtain information about the position and deformation of the high lift components. The gap between the wing trailing edge and the flap influences the aerodynamic performance of the high lift system distinctly. A variation of the flap gap due to a change of the wing load affects the flow of the flap, especially as far as flow separation is concerned. Thus gap variation has to be considered for a complete analysis of the flow characteristics of the flaps.

The Edge Detection Technique (EDT) is an optical measurement system, which has been developed for the flap gap observation on an Airbus A340-300 test aircraft in the frame of the EC – funded project AWIATOR. For this purpose a special multi camera system was established to fulfil the requirements of flight testing. The cameras were installed in the aircraft cabin using the windows behind the middle door as optical access to the flaps. Markers applied on the spoilers, which form the main wing trailing edge, and on the flap were used to obtain the gap variation with respect to a ground reference. In the first flight test campaign each camera had its own observation area, so four different spanwise areas could be observed.

For the second flight test campaign an advanced EDT system was used. Because it is not possible to obtain 3D – information from a single image without additional information and assumptions, this time the EDT system was set up as stereo system, so the 3D – position of the markers on the wing could be determined.

In order also to obtain information on the deformation of the wing the Image Pattern Correlation Technique (IPCT) has been employed as well. A first feasibility test of IPCT in flight using a single camera showed promising results. For a further development of IPCT in flight testing ground tests on the Dornier 728 prototype were performed. This experiment investigates the feasibility of stereo IPCT with the boundary conditions of an in – flight setup.

1. THE CAMERA SYSTEM

Flight testing implies special requirements to measurement systems, which include the boundary conditions for the hardware as well as the operation of the system. Therefore a dedicated multi-camera image acquisition system has been developed [1]. This system is based on a 19” industrial computer and a monitor – keyboard unit which were rack - mounted in the aircraft cabin. The universal power supply unit with automatic voltage detection can handle the power condition of the a/c (110V, 400 Hz) as well as the standard power supply (220V; 50-60 Hz).

In the first F/T campaign the system was equipped with four small-sized progressive scan CCD cameras of type CV – M10 manufactured by JAI with a resolution of 780 x 580 pixels and a maximum frame rate of 25 Hz. In the second F/T campaign they were replaced by high resolution cameras of type CV – A1 (1390 x 1040 pixel) to increase the accuracy of the results. The maximum frame rate of the CV – A1 camera is 15 Hz. So depending on the used camera the system can resolve events up to 7.5 Hz or 12.5 Hz in time. The camera system can handle up to four cameras simultaneously, so this number was used in the F/T, too.

FIG 1. EDT cameras mounted on XS95 profile beam behind the A/C window.

During the F/T the system had to operate fully automatically. A manual operation was not possible due to security reasons. The image sequence acquisition was started by means of a remote starter box, which was placed at the desk of the flight test engineer. The system used the daylight for the illumination of the targets on the wing, thus the illumination varied strongly, depending on the position of the sun with respect to the a/c or if there is blue or cloudy sky. Therefore, an automatic exposure control was integrated in the image acquisition software, which enabled optimal exposed frames independent of the illumination conditions.

2. MEASUREMENT METHODS OF EDT

The four cameras have been placed in the aircraft cabin of the Airbus A340 – 300 using the windows behind the right middle door as optical access to the wing. They were mounted on an optical X95 - profile beam with a length of 3 m, which enables a flexible positioning of the cameras over its range.

2.1. Evaluation of single images within the first F/T campaign

Within the first F/T campaign, each camera had its own observation area; hence from the point of view of the evaluation it was a multiple mono camera system. A picture of the wing in full flap configuration is given in fig. 2. The observation areas of the four cameras are framed to mark their position.

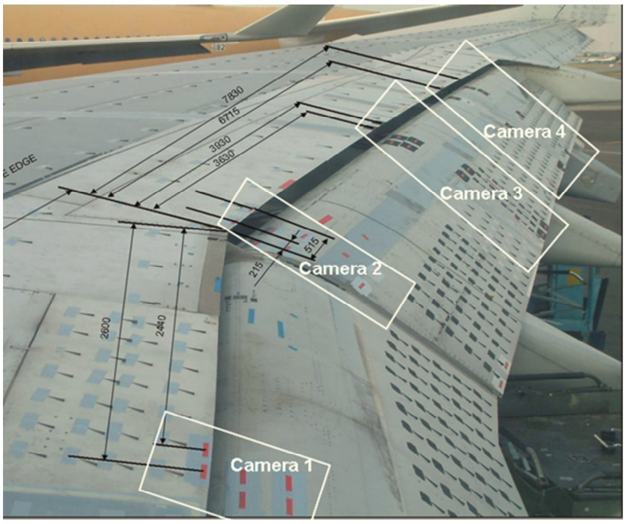

FIG 2. Position of the EDT targets on the wing and cameras' fields of view

Fig. 3 shows an exemplary image of one of the cameras. Pairs of stripes aligned parallel to the wing trailing edge were used as EDT targets. The stripes had a wide black border to ensure a good marker contrast to the surrounding. The positions of the targets were evaluated relatively to a ground reference. Therefore, a reference picture of each single camera, for each flap position was recorded on ground. For calibration purposes of the EDT system a vertical grid plane was used (Fig. 4). It was supposed that the movement of the targets, caused by the wing deformation are in the calibration plane and that the movement out of plane are negligible. The calibration grid was oriented perpendicular to the ground. From the calibration images the direction and scale of the vertical and horizontal target displacement were determined. The vertical displacement is a measure of the bend of the wing accompanied by an inboard directed horizontal displacement.

The evaluation of the gap variation was carried out in the following steps.

1) Determination of the target positions within the image for the ground reference image as well as for the in-flight recordings.
2) Determination of the vertical and horizontal displacement of the targets measured in flight compared to the ground reference with the same flap configuration using the calibration data.
3) Calculation of the gap variation by subtracting the vertical displacements of the targets on the flap from the displacement of the spoiler targets.

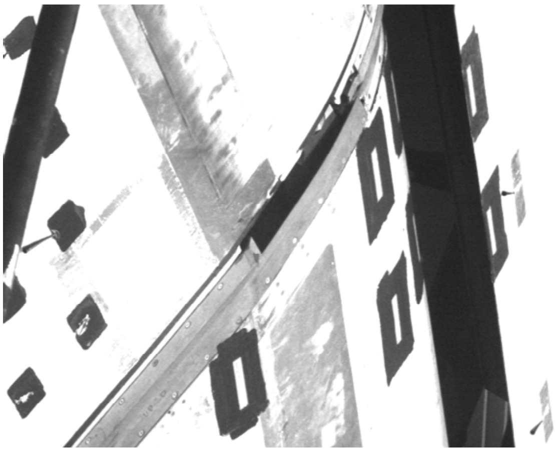

FIG 3. Exemplary image of EDT camera no. 2. The black bordered stripes were used as EDT targets.

Fig. 4 shows the first evaluation steps by means of a calibration image. The coloured dots mark the detected position of the markers on the ground (blue) and in-flight (red). Because the displacements of the markers were assumed to be in the calibration plane, the vertical and horizontal displacement could be derived from the pixel displacement of the marker positions.

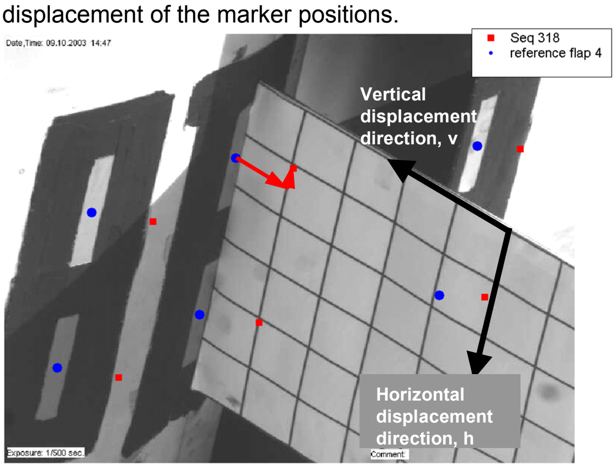

FIG 4. Calibration image with marked target positions of ground reference (blue) and F/T (red) of camera no. 1.

The accuracy of the target detection algorithm calculated from the evaluation of a sequence of 300 images recorded on ground was ±0.5 mm for camera 1 and 2, ±0.8 mm for camera 3 and ±1.2 mm for camera 4. In particular, the EDT results on the outer flap led to the conclusion that the chordwise movement of the flap with respect to the wing is not negligible, as it was assumed before. Therefore, it was decided to change the measurement concept in the second flight test campaign towards a stereo camera system. Using a stereo system the 3D position of the markers can be determined without the necessity of additional assumptions.

2.2. Advanced Stereo EDT

For the advanced stereo – EDT system the four cameras were arranged as two stereo systems observing two areas on the outer flap. In addition to the camera resolution, the scale and the accuracy of the marker detection algorithm, the accuracy of a stereo system depends on the stereo angle α between the cameras [1]. The depth resolution improves with increasing stereo angle up to an optimum of 90°. On the other hand a stiff connection between the cameras has to be guaranteed, because any movement between the two stereo cameras will decrease the quality of the calibration. Hence, the cameras were mounted on the same camera support as used in the first F/T using the full length of the 3 m profile beam. Finally a camera basis of 2.2 m could be reached, which corresponds to a stereo angle of nearly 9° or 10.5° for the two fields of view at the spanwise position of 12 m or 14 m on the wing. This small stereo angle notwithstanding an accuracy of 2 mm in depth could be guaranteed and the in - plane accuracy is better then 0.5 mm.

The stereo recordings were evaluated using the image processing software DaVis by LaVision. Both stereo systems were calibrated by recording a calibration plate at different arrangements placed within the measurement volume. From the known size of the calibration grid the internal and external camera parameters are determined.

For the stereo evaluation white circles with a diameter of 20 mm and 25 mm on a black background were used as targets. A single target was nearly of the size of a postcard. The camera image in Fig. 5 shows the targets on the spoiler and the flap. Five markers were located in a group on the spoiler and five further markers were placed on the flap. The area of a target group is small enough that the relative coordinates of a target to each other do not change significantly.

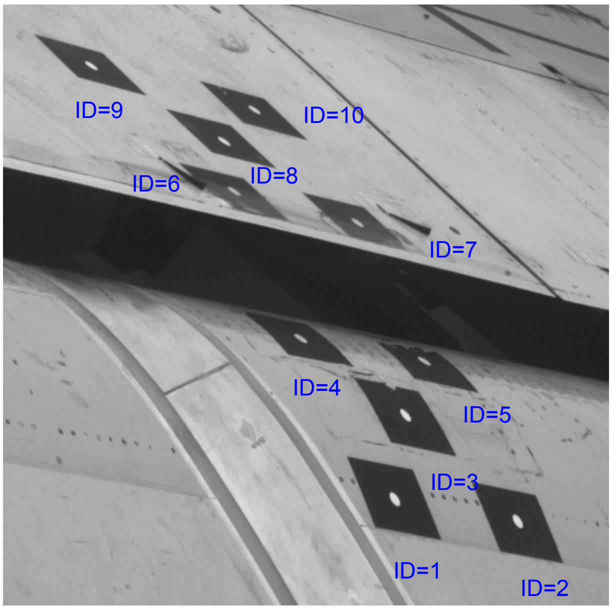

FIG 5. EDT targets on flap and spoiler, the fixed ID numbers are written in blue.

The evaluation software DaVis detects the pixel position of the markers in the single images and calculates the 3D coordinates in a camera fixed coordinate system using the triangulation algorithms of photogrammetry. The target coordinates on ground were used as reference model coordinates to enable a clear identification of the markers. This is possible due to the irregular positioning of the markers and the fixed relative positions of the target groups. All markers got an ID number, which is displayed in Fig. 5, too.

The determined target coordinates were transferred in the A/C coordinate system. Fig 6 shows an example of the measured targets of the ground reference (red) and the target position of a recording in flight (green). For a better visualization the single targets were connected with faces, which form a plane on the spoiler and a small pyramid on the flap caused by the flap curvature.

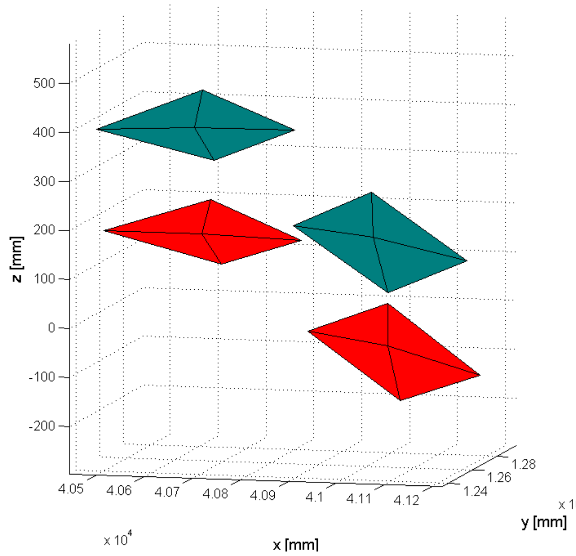

FIG 6. Measured EDT target position on ground (red) and in flight (green).

For every test point of the flight test an image sequence of about 170 frames were recorded. Within one time series the target positions show a variance of up to 50 mm for the area at the span of 14 m, which is caused by vibrations of the wing and the cameras. Nevertheless, those errors of the absolute target positions do not influence the analysis of the gap variation, because the relative distances between the markers are not influenced by the vibrations.

In the next evaluation step the flight test results were fitted to the ground reference by optimization, so that the spoiler targets of the flight data match with the spoiler targets of the ground reference. This finally yields the relative movement between flap and spoiler, which is a measure of the gap variation. Fig 7 shows the same data as in Fig 6 with the flight data fitted to the ground reference. One can see that there is a small increase of the gap in z – direction, but the relative movement towards the nose and the fuselage is of much higher order. The standard deviation of the transformed marker coordinates in a time series of a measurement point is smaller than 1.5 mm now.

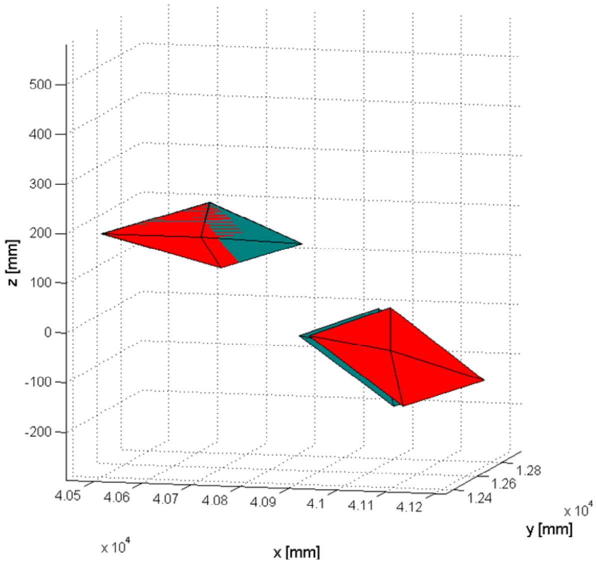

FIG 7. Measured EDT target position on ground (red) and the in flight result (green) fitted to the ground reference.

The differences between the 3D-coordinates of the ground reference and the fitted flight data (see Fig. 7) give information about the relative movement of the flap and the spoiler compared to their ground position.

The results show that for both observation areas the movement in z – direction of the flap with respect to the spoiler is marginal compared to the spanwise (y) and chordwise (x) displacement. These displacements have a higher order of magnitude and reach up to 20 mm compared to the maximum z-displacement of 3 mm. That means that the changes of the flap gap results mainly from a change in the overlap between spoiler and flap instead a change in the gap width.

The EDT results of the second flight test campaign showed that the movement of the flap in the x- direction is not marginal compared to the movement in y- and z-direction. For the EDT evaluation of the first F/T campaign, it was assumed, that the chordwise movement of the flaps with respect to the spoiler is negligible. The stereo – EDT measurements of the second F/T campaign, which deliver the full 3D movement, couldn't verify this assumption.

3. IPCT PRE - TEST WITHIN AWIATOR

Image Pattern Correlation Technique is an optical deformation measurement method derived from Particle Image Velocimetry (PIV). In PIV the velocity vector is determined from the particle displacement between two images recorded with a known time difference by means of cross correlation [6]. IPCT uses the same algorithms to determine the deformation. Therefore, a correlation pattern of random dots is applied on the surface of the measurement object instead of single markers as used for EDT.

During the first flight test campaign a first in-flight IPCT test was performed placing a pattern of the size of a DIN A4 page on the flap in the view of field of a camera. The cross correlation routines deliver the displacement of the pattern in a camera image caused by deformation of the test object. With a single camera set-up, such as used in this pre-test, the displacement of a surface relative to a reference status can be determined. The displacement vector field is calculated by cross correlation of the measurement image with a reference image. As an example a flight test data point acquired in clean flap configuration was evaluated. In Fig. 8 the reference and the measurement images are superimposed. For a better correlation an offset of 70 pixels in the x-direction between the pictures has been applied. The calculated pixel displacement between the frames is plotted as a vector field.

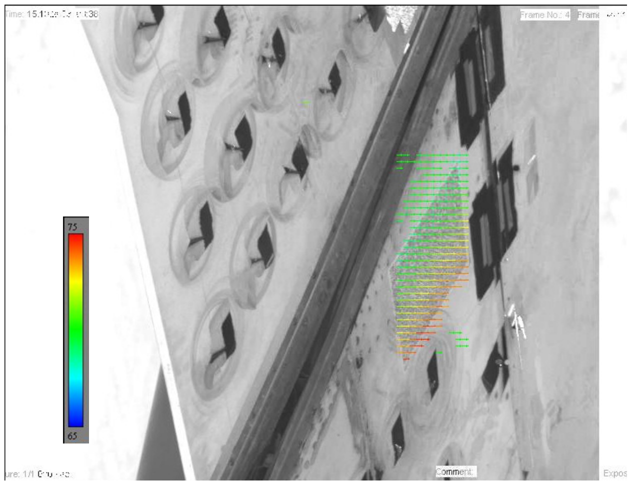

FIG 8. Superimposed reference and measurement pictures and the pixel displacement vector field. The magnitude of the displacement vectors is colour-coded.

Analogue to the EDT evaluation, the horizontal and vertical displacement were calculated from the pixel displacement vector. The result is plotted in Fig. 9. It matches well with the vertical shift calculated for the EDT target nearby. The continuously increasing bend of the wing in spanwise direction can be seen clearly. It amounts to nearly 5 mm over the 200 mm width of the dot pattern area.

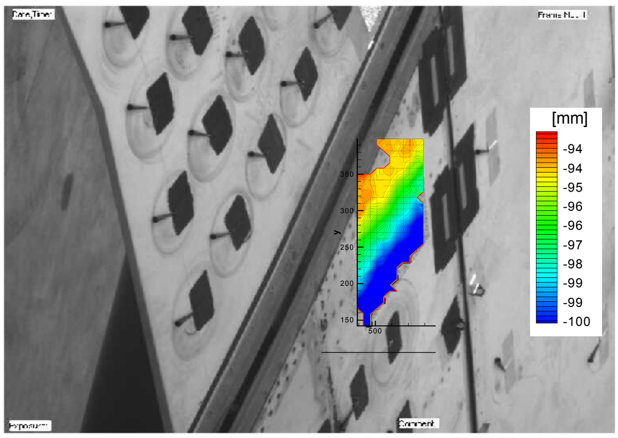

FIG 9. Exemplary IPCT result: vertical shift [mm] calculated with the EDT calibration parameters plotted over the reference image.

4. STEREO IPCT GROUND TEST ON DO 728

The above described optical measurements demonstrated the feasibility of a stereo camera setup for position detection, under the limitations of flight testing, in particular concerning the optical access to the measurement area. The IPCT test using a single camera delivered promising results. In a further development the feasibility of Stereo IPCT was investigated on the Do 728 prototype at the DLR in Göttingen on ground.

Stereo IPCT is already applied successfully in wind tunnel testing to determine for instance the wing deformation of models [4][5]. Considering flight tests the possibilities of setting up a stereo camera system are strongly limited because the only location for a camera installation is the a/c itself. The simplest approach is to install the cameras behind a cabin window, as already done during the above described EDT measurements within AWIATOR. However, due to the dimensions of the fuselage the viewing angle between the camera line of sight and the wing surface is very small. That results in strongly distorted images of the wing surface, which again influences the accuracy of the measurement. For this reason a ground test was conducted to prove whether aileron deformations could be measured during flight and which setup parameters considerably influence the measurement results. For an optimal stereo IPCT setup the cameras have to be placed above the wing. The stereo angle between both lines of sight should be about 40°. Figure 10 shows a draft of the two stereoscopic camera setups used during the test.

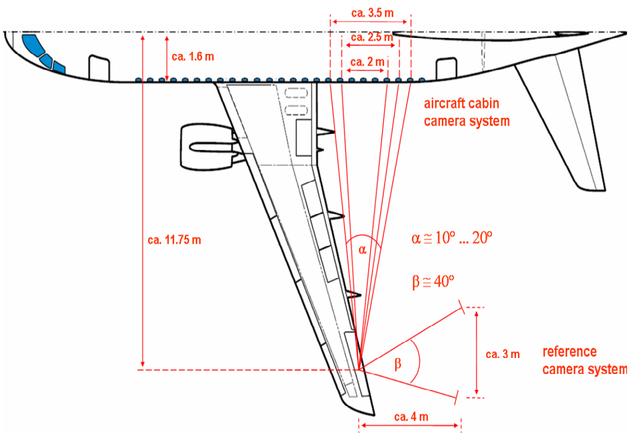

FIG 10. Top view of the Do 728 including the camera setups during the Stereo IPCT measurement.

It can be seen that the camera system installed in the aircraft cabin has a very small stereoscopic angle. This angle could be varied in a range of 10° to 20° due to the variability of the camera base. To cross check the results a reference camera system with a more ideal setup was placed above the wing.

In contrast to EDT a stereoscopic IPCT measurement setup enables the measurement of the shape of the absolute surface of a spatial test object. Therefore, the Stereo IPCT combines the cross correlation algorithms with the calibration and triangulation algorithms of the photogrammetry, which were also used for stereo EDT. Further on, IPCT uses a random dot pattern applied on the target surface instead of single markers. Thus, it delivers the 3D surface of the test object and in a further evaluation step a 3D deformation vector field with respect to a defined reference.

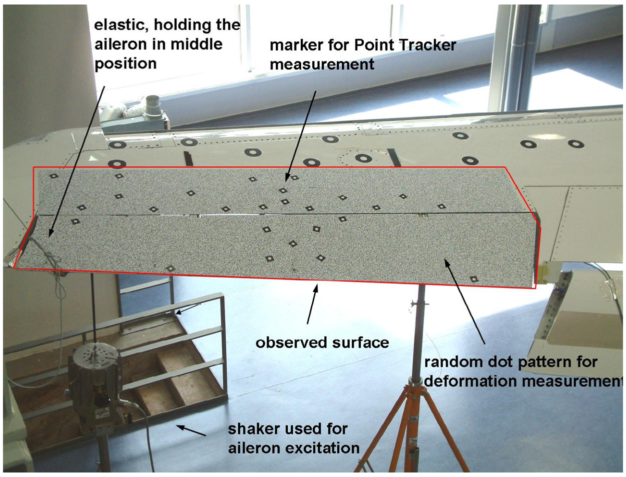

FIG 11. Area of interest during the Stereo IPCT measurement.

Figure 11 shows the applied random pattern on the area of interest on the wing. The markers in this area were used for further position detection measurements.

Within the test a deformation was simulated by deflecting the aileron in a range of ±5°. The results of this measurement are presented in figure 12.

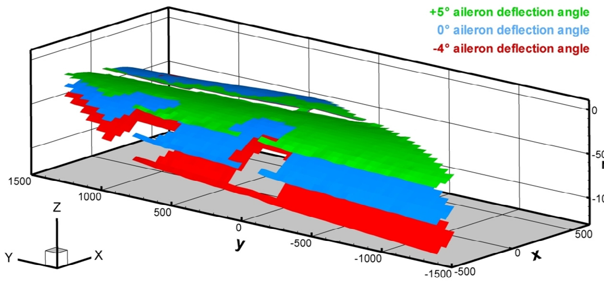

FIG 12. Aileron surfaces derived from the computed deformation vectors.

It shows the aileron surfaces at three different deflection angles computed in the following way:

- Computing the height of the reference surface, in this case the aileron at an angle of -5°.
- Determining the 2D displacement vectors between the reference surface and the aileron surface at -4°, 0° and +5° for each camera.
- Computing the 3D deformation vectors using the 2D displacement vectors and the camera mapping function.
- Summing up the corresponding deformation vectors to the reference surface.

It can be seen that the surfaces could be determined well. Furthermore, the determined 3D deformation vectors were used to compute the aileron deflection angles. The results in figure 13 show that the measurements of the aircraft cabin camera system stay very close to the results of the reference system. The angles measured by a wing integrated potentiometer confirm the results of the Stereo IPCT measurements.

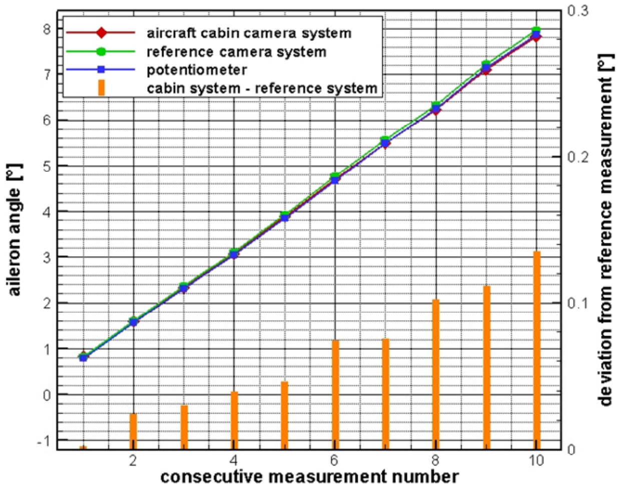

FIG 13. Aileron surfaces derived from the computed deformation vectors.

In conclusion it can be said that Stereo IPCT is applicable to measure 3D deformations under flight test conditions.

5. CONCLUSION

Within the flight test of AWIATOR the optical measurement system EDT was used to observe the flap gap. During the project the technique was improved continuously. In the first approach the system based on the evaluation of single images, which necessitates additional assumptions. For the second flight test campaign the concept was changed to a stereo setup. The real 3D data obtained from this test were more reliable, because no assumptions had to be made. In fact the stereo results proved that the outer flap region mainly moves towards the wing nose, whereas in the single frame evaluation this component was assumed to be negligible. Also the calibration of the system was improved, which includes a simplification of the procedure as well as a better accuracy of the volume calibration. The integration of new high resolution cameras also contributes to an improved performance of the system.

Within AWIATOR the feasibility of a stereo camera system and IPCT with the demands of flight testing was demonstrated successfully. The ground test measuring of the aileron deformation at the Do 728 prototype by means of stereo IPCT combines both. The ground test allowed a detailed investigation of the accuracy of the setup. The given deflection angles of the aileron, which were used as well defined deformation, could be reproduced well using the IPCT results. In conclusion, the applicability of stereo IPCT in flight testing seems to be feasible.

IPCT delivers very detailed results, because it uses the random dot pattern as target, so the deformation of the complete surface is obtained instead of the displacement of single markers. Delivering more information IPCT evaluation is more time - consuming than EDT. So for a detailed deformation analysis the application of stereo IPCT can be recommended, whereas for simple position detection a marker based technique is sufficient.

A further development toward the combination of position detecting, using single markers and IPCT is in progress. This approach will increase the range of application of IPCT. It enables a recalibration of vibrating cameras and a realignment of the cameras between the acquisition of the reference image and the measurement image. This is of importance for deformation measurement in the wing tip region, where the wing position changes considerably between the ground reference and the in-flight measurements due to the bend of the wing.

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