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# Enhancement of the Stereo Pattern Tracking Technique for Model Deformation Assessment at ETW

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**The European Transonic Windtunnel (ETW) is a pressurised cryogenic facility adapted for testing cruise or high lift configurations of aircraft models at flight conditions. A high stability of test conditions, excellent repeatability and a wide test envelope of Mach and Reynolds numbers (Figure 1) are some of the main criteria for numerous customers of the worldwide aircraft industry for using ETW. Therefore developments of new and improvements of operated measurement systems are an important feature of the research activities for responding to clients' requirements. Performing aeroelastic investigations or operating at increased tunnel pressures combined with high lift loads may lead to deformations of wings, high-lift components or tailplanes in form of twist and bend variations which need to be known for a proper analysis and understanding of the acquired aerodynamic data.**

**To provide information about the model shape, ETW has developed the Stereo Pattern Tracking technique (SPT) using thin dot type markers attached to the lower surface of model components. Over the past decade ETW has permanently enhanced and improved its systems. Presently, there are four SPT-Systems available differing in the frame rate or image resolution. Each SPT-System uses a pair of cameras in stereoscopic arrangement. Productive data are typically acquired in pitch/pause mode during a lift polar but may also be collected during a continuous model pitch with a maximum pitch rate of 0.15deg/s.**

**This paper gives an overview on the different SPT-Systems, their analysis under severe test conditions and documents the development and improvement of the SPT measurement technique.**

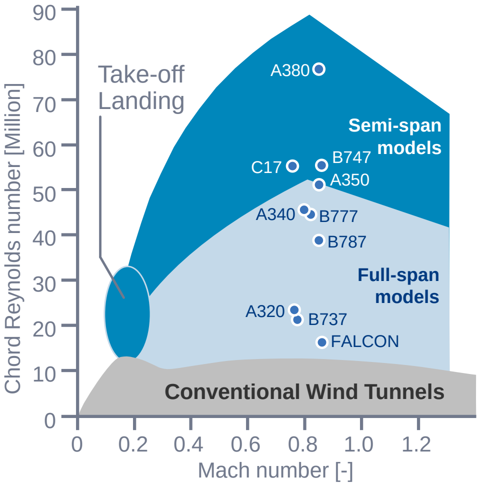

**Figure 1:** ETW Performance Envelope

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# I. Introduction

The European Transonic Windtunnel is a continuous flow windtunnel with a test section of 2.0m x 2.4m and a Mach number range from 0.15 to 1.3. The facility operates within a temperature range of 312K to 110K and a pressure range from 125kPa to 450kPa. The opportunity of separating Reynolds numbers effects or pure aeroelastic effects lead to different envelopes.

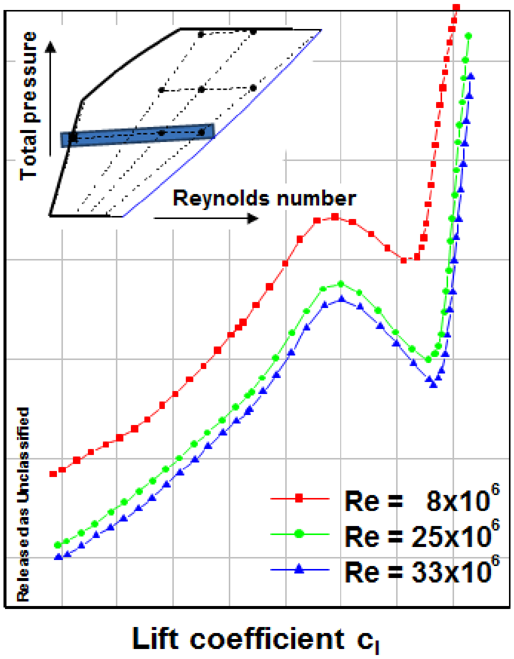

**Figure 2:** Reynolds variation at const. airloads

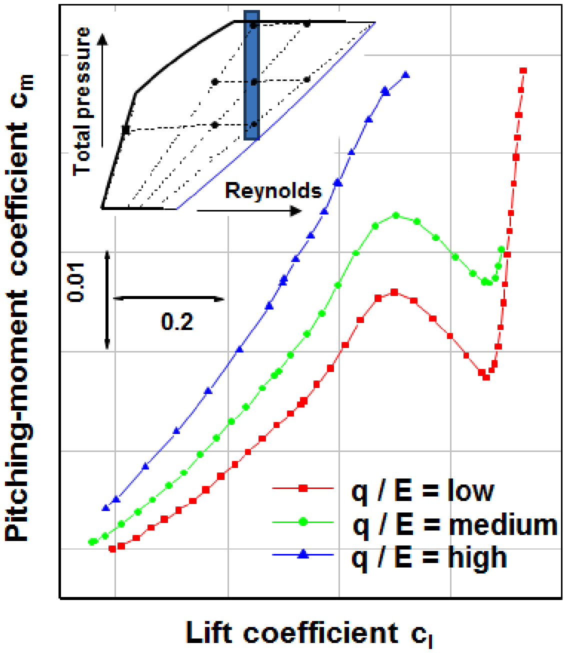

**Figure 3:** Airloads variation at const. Reynolds

Performing pure Reynolds number investigations the ratio of q/E has to be kept constant by adapted combinations of tunnel pressure and temperature. Aeroelastic analyses require operating the tunnel at a constant Reynoldsnumber. This can also be achieved by variations of the tunnel pressure and temperature. As the Young’s modulus is slightly dependent on temperature this has to be considered for the individual operational tunnel set points.

High flow velocities can generate several tons of loads on airfoils. Wings exposed to those loads respond with bending or torsion due to sweep and spanwise load distribution. Nowadays, CFD coupled with structural codes are numerically predicting wing or component deformations but with limited accuracy. Striving for a direct comparison of aerodynamic CFD and wind tunnel results detailed knowledge of the wing shape at test conditions is mandatory. To provide relevant information the Model Deformation Measurement System MDMS was developed in collaboration with DLR around the end of the last century. This method is based on the Moiré fringes technique[1]. The MDMS was designed for full model testing at ETW only and a new system, the so called SPT-Method was required and developed for deformation measurement on half models. In between, SPT-systems are applied for half- and full-models.

This paper provides general overview of the Stereo Pattern tracking technique, explains the different System, the measurement setup as well as the data reduction setup and present exemplary results of the operational system and the commissioning of the new high SPT system.

## II. Stereo Pattern Tracking

### A. Measurement principle

Deformation assessment is based on the model observation by a stereo camera system. They are installed under a perspective of about 70° in the side-, top- or bottom-wall whether depending on the model type. The existing variety of objectives provides the capability for a complete coverage of the field of view, e.g. flap, slat or the whole wing. The achievable measurement accuracy is better than ±0.1 deg in twist and ±0.1mm in bending. Deformation measurements simply rely on the space wise shift of individual markers attached to the components to be monitored. Letraset markers (black dots surrounded by a white ring, diameter approx. 10mm) available in different sizes of about 7µm thickness are used. These markers have been selected and qualified for the harsh operating environment of ETW (dry air, cryogenic temperatures, increased pressures).

Presently, there are 4 SPT-Systems available for deformation measurements. SPT-1 and 2, the basic systems, are identical and acquire data with a framerate of 5Hz. One year ago a new system SPT-3 was procured and installed operating with 25fps (frames per second). The most modern system D-SPT 4 designed for an assessment of dynamic deformations features a frame rate of 384,6Hz. Hence, the system is able for tracking an airfoil executing movements up to half of the framerate according to the Nyqist-Shannon-Sampling theorem. Table 1 provides technical details about the 4 different SPT-Systems.

| **System** | **SPT 1 & 2** | **SPT 3** | **SPT 4** |
|---|---|---|---|
| **Company** | Vosskuehler | Toshiba Teli Corporation | Vosskuehler |
| **Kamera** | CCD-4000/C | CSC12M25BMP19-01B | CMC-4000 |
| **Resolution** | 2048(H)x2048(V) | 4096(H)x3072(V) | 2320(H)x1728(V) |
| **Pixel size** | 7.4µm x 7.4µm | 6µm x 6µm | 7µm x 7µm |
| **Megapixel** | 4MP | 12MP | 4MP |
| **Frames per second** | 5fps | 25fps | 386fps |
| **Sensor** | CCD | CMOS | CMOS |
| **Scanning area** | 15.15(H)mm x 15.15(V) mm | 24.576mm(H) x 18.432mm(V) | 16.24(H)mm x 12.1(V)mm |
| **Gain** | Video 1 or 2 (+6dB) | Digital 0 to +18dB [180step] | Digital 0 to 2 - 8Bit of 10Bit are read out |
| **Shutter speed** | Up to 1/10000 sec | Up to 1/20000 sec | Global shutter |
| **Digital output** | 12-Bit | 8- or 10-Bit | 8-Bit |

**Table 1:** Overview of the 4 SPT-Systems

### B. Camera Installation

Obviously, commercial cameras are built for an operation at ambient conditions and are unable sustaining in the pressurised, cryogenic environment of ETW. It turned out that most of them are able surviving pressures up to 4.5 bar but require warm, temperature controlled housings for a reliable operation in the cold. Hence, cylindrical insulated boxes with internal heater foils and temperature control equipment have been designed and manufactured.

Figure 4 shows an example of the insulation cover made of Polyurethane and the roof top fabricated of special wood throws a glance from the plenum at the installation in the top-wall with its supporting structure.

**Figure 4:** Camera housing SPT3

**Figure 5:** Camera installed in the Top-Wall

In former times the setting of camera focus and aperture had to be completed prior to the installation of the housings in the test section walls. Varying tunnel temperature and pressure the density of the test gas may increase up to a factor of 14 thus affecting optical systems. Additionally, the illumination of the test section may have to be adapted resulting in a remarkable change of the optical situation. Increased light reflections on the shiny metallic surfaces of the model can further contribute to unacceptable situations for the cameras leading to a loss of their capability for identifying the markers. The required setting can only be achieved from outside the tunnel by remotely controlled devices. Consequently, ETW has designed remote controlled devices to adapt focus and aperture by installing small stepper-motors, small gearboxes, lever arms and tooth belts as shown in Figure 6 and 7.

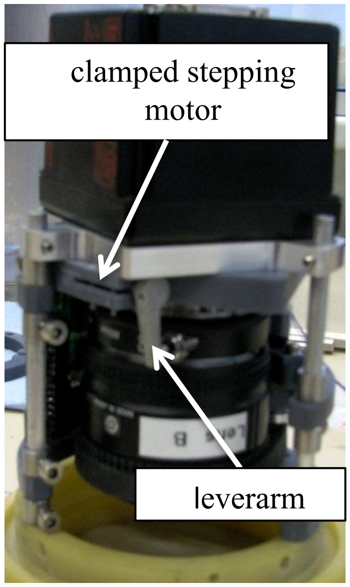

**Figure 6:** aperture control

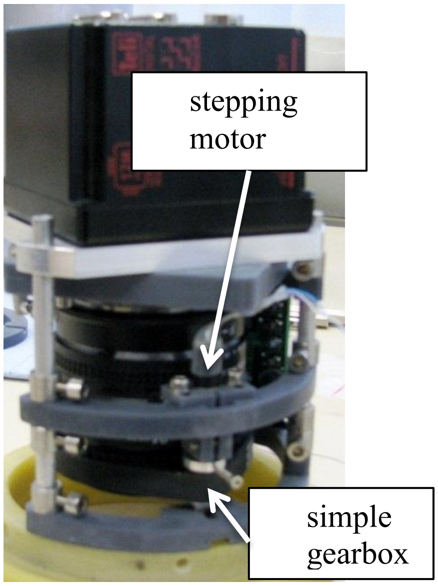

**Figure 7:** focus setting

The enhanced capabilities generated images of increased brightness thus providing a higher contrast between markers and background leading to an easier detection of the markers by the SPT software.

## C. Calibration procedure

### 1 Lens calibration

Before starting a model deformation measurement with a stereo-camera-system an adjustment of the lens distortions has to be performed. Each lens has a geometric distortion which can be explained by a concentric circle being reproduced as a circle with a distorted radius. Two kinds of distortions (or κ-values) are known: a positive κ called pillow distortion and a negative κ named barrel-pillow-shaped distortion (Figure 8 and 9)

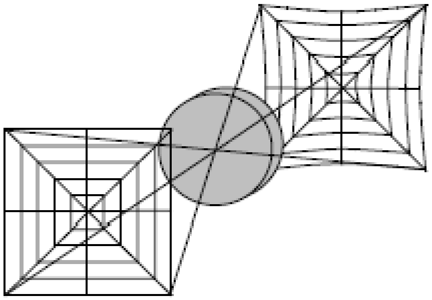

**Figure 8:** pillow distortion

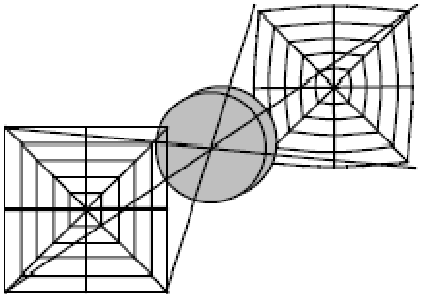

**Figure 9:** barrel-pillow-shaped distortion

Considering basic squares (Figure 8 and 9) all lines are straight and should appear straight again in the projection. In reality we will find an inward/outward deformation in the outer region of the images. In order to avoid such distortions a second order polynomial correction function has to be evaluated requiring a camera alignment in all three axes. Using the resulting calibrated position all lines can be numerically reconverted into straight lines.

### 2 Position calibration

Once eliminated, the positioning of the finally installed cameras has to be calibrated. A very accurately manufactured calibrated frame is used for defining the coordinate system for determining the marker coordinates within a 0.1mm. ETW owns different frames for covering the space envelope for wings and smaller model parts. Each frame is equipped with 32 bulbs and manufactured with high precision for guaranteeing scaling and angularity of the marker system. Any frame rotation against the model system is not detectable during the camera calibration but is taken into account by the data reduction using the marker coordinates from the no-wind traverses performed in the tunnel at the beginning of each test campaign.

The calibration procedure requires an installation of the model plus the calibration frame in the test section. A subsequent automatic identification of the bulbs is achieved by varieties of the grey-scale values. Every time the camera takes a picture those receptions are digitalized with 8bit. This means every reception can be divided into two 256 grey-scale values. Switching on a bulb the grey value is set to a value of 256 equivalent to white in the color spectrum. During calibration the tunnel light is switched off causing a black background and resulting in a grey-scale value of zero. This maximum difference in grey-scale values represents the key factor for achieving the high accuracy of better than 0.1mm in the assessment of the marker positions in space.

### D. Marker Setup

The model deformation measurement system is based on the tracking of predefined markers attached to the model surface. Depending on the observed model area the markers vary in size, they have a thickness of 7 µm and are matt to minimize disturbing reflections. Each SPT system is capable to track and determine the three-dimensional spatial coordinates of up to forty markers.

In standard applications the forty markers are uniformly distributed on the leading and the trailing edge of the model part e.g. the wing. For special applications like gap measurements the marker arrangement is different by applying four lines of markers e.g. two on the main wing for reference purposes and two on the flap. Hence, it is possible to determine the relative deformation between the two model components. Figure 10 shows the a model prepared for the simultaneous operation of three SPT system, one looking on the main wing, one measuring the flap deformation and one the Krueger flap movements.

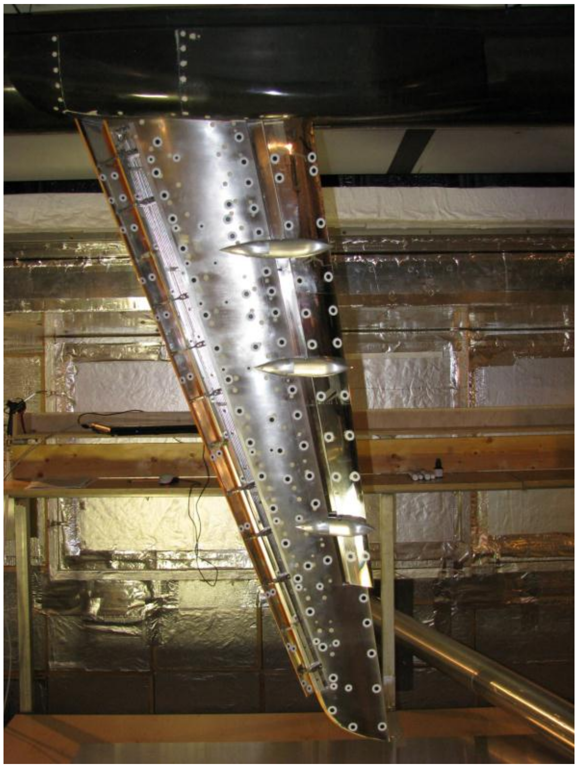

**Figure 10:** DeSiReH Model equipped with Markers

### E. Measurement

SPT system software tracks the predefined markers using the stereo images and calculates the three dimensional coordinates of the markers based on the calibration. In addition to the coordinates the SPT system determines an error code for each marker indicating if the marker coordinates are valid or questionable. Together with the marker coordinates the error codes are transferred to ETW’s high level acquisition system, where the data are stored and synchronized with all other measuring data. In the next step the acquisition system performs basic calculations for assessing real-time bend and twist values during the measurement. These “raw” values allow a first verification of the measurement, while the final analysis requires additional post-processing using ETW’s data reduction.

The standard procedure for SPT measurements is to perform pitch/pause polars to average several SPT dataset and therewith reduce the influence of disturbing optical effects. These effects noticeable by data scatter are increasing with decreasing temperature and rising pressure because of changing density within the test section. This approach provides the highest possible data quality. This pitch/pause traverse is also done under no-wind condition, to get the reference data of the unloaded model.

Depending on the tunnel, lighting and model setup also measurements in continuous pitch mode could give comparable results as some test during the last months show, so that in some cases this could be an alternative. But because this application is relatively new, additional tests are required and some adaptations have to be done to the data reduction to finally validate the data quality.

## F. Data reduction

The post-processing of the measured coordinates is the final step of the deformation measurement and can be separated in two steps. The first step is the analysis of the no-wind reference data, while the second step is the final assessment of the deformation data.

### 1 Wind-off

The markers are moving on vertical circles around the axis of model rotation. Deviations from observed marker coordinates from perfect circles are small but have to be corrected. Those deviations are caused by temperature and gas density effects. The translation of marker coordinates into model coordinates is determined by reference markers which are manually measured in the model system. Using appropriate mathematical function allow the evaluation of the point of model rotation, the 3D-coordinates of each marker for the model at zero incidence and the misalignment of marker-coordinates system (misalignment of calibration frame) to the model system. After this process the measurement quality can be checked by the bend and twist values of the no-wind traverses, which have to be close to zero. If these checks are verified the evaluation of the wind-on data can be started.

### 2 Wind-on

Evaluation of wind-on data consists of different iterations. In a first step the misalignment between SPT calibration system and model system is corrected to avoid any misinterpretation of results. For example a small misalignment round the z-axis would results in a wrong twist value, because a part of the wing bending slope would be interpreted as wing twist. In the next step the marker coordinates are transformed by a rotation around the point of model rotation by the measured model incidence to eliminate its influence. The last step before starting the fitting is a subtraction of the z-coordinate of the no-wind evaluation from each marker resulting in the displacement in z-direction for each marker. Now a 2D-polynomial is evaluated fitting the displacements of all measured markers as function of the horizontal plane coordinates x and y. Using an iterative process to eliminate outliers. Different boundary conditions, e.g. the wing bending at the fuselage should be zero, are used to improve the 2D-fitting function.

For special applications like gap measurements the post-processing procedure has to be slightly adapted while keeping the basic principles.

## III. Current ETW SPT Test Results

The procurement of the SPT 3 system was driven by the objectives for providing a better coverage of high lift configurations and the replacement of pitch/pause measurement by a continuous pitch one. A comparative test is illustrated in Figure 13. The classical approach called pitch/pause is acquiring marker positions over a limited period at different model incidences. Subsequent data averaging results in distinct values per incidence leading after a polynomial curve fitting to a line as indicated in Figure 11. Operating the new system SPT 3 with its enhanced capabilities during a continuous pitch of the model the acquired raw data indicate identical results without further mathematical treatment. Comparative relevant data taken with SPT 1exhibit an increased data scatter and waviness of the behavior of the marker shift.

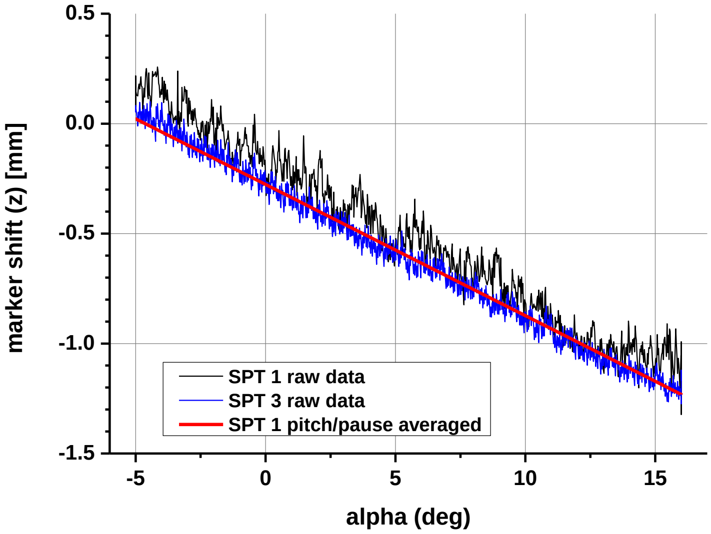

**Figure 11:** Comparison of SPT system capabilities

Since several years model deformation assessment in ETW using SPT systems is a standard routine applied on the main wings of full and half-models. The individual wing bending and twist as function of the dynamic head and the acting lift is exemplarily given in Figure 12 and Figure 13. The resulting increase in lift when pitching the model up

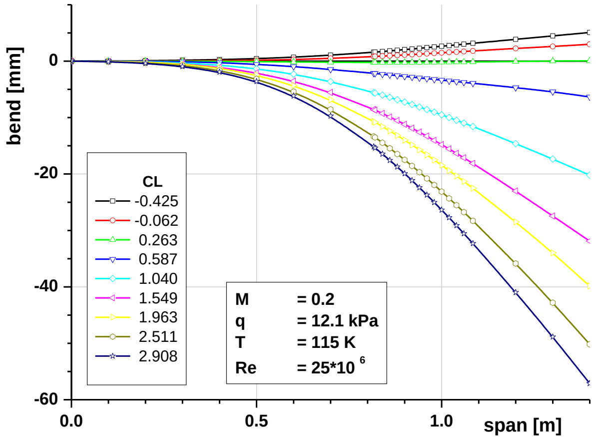

**Figure 12:** Wing bend measured by SPT 2 System

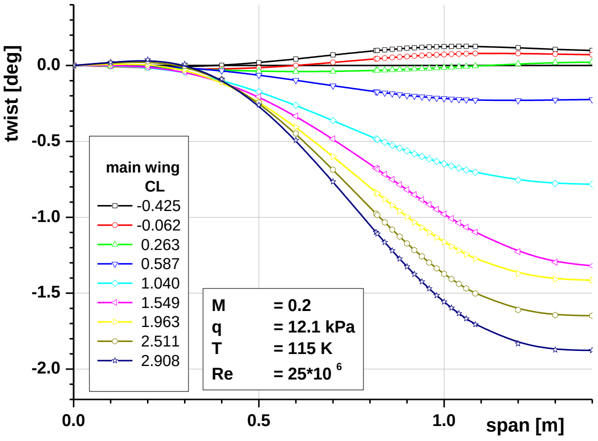

**Figure 13:** Wing twist measured by the SPT 2

causes raising wing deformations. Considering the flight Reynolds number case at 25 million generated by combining a tunnel pressure of 4.1 bar and a temperature of 115 K at M=0.2 the wing tip suffers a maximum upward bending of 50mm (Figure 12). The according wing twist given in Figure 13 reflects the existing spanwise lift distribution as a function of the model incidence. A maximum twist of 2 deg has been assessed quoting an accuracy of ±0.1 mm in bend and ±0.05 deg in twist (Figure 14).

The first simultaneous operation of all 3 SPT systems was performed along the wind tunnel entry within the EC-project DeSiReH[6]. A half model featuring a wing of natural laminar flow design combined with adapted high lift devices as shown in Figure 14 was equipped with series of markers for deformation assessment by SPT on the main wing and flaps as presented in Figure 10.

Due to the complexity of the involved measurement techniques (PIV, TSP and SPT were operated in the same campaign) and the reduced capabilities of the old SPT systems an individual pitch/pause measurement was done for deformation assessment. The system setup defined SPT 1 for monitoring the complete wing while the other two systems focused on the flap and Krueger device. With respect to Figure 10 it is important addressing the flap configurations: The Krueger flap consists of 3 spanwise and the downstream flap of 2 individually elements linked by pairs of dowel pins. A view on the model with its orange TSP coating on installed in the test section is given in Figure 14.

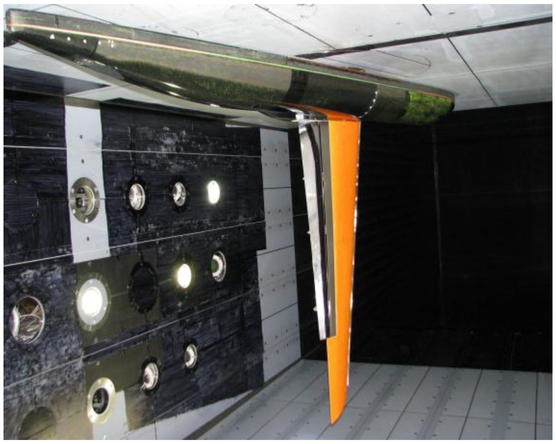

**Figure 14:** The DeSiReH half model in the ETW test section

It should be noticed that the main wing revealed being pretty stiff with respect to other models tested leading to small deformations only but allowing an impressive demonstration of the system capabilities. Regarding the assessed combined wing-flap twist for variations in model lift given in Figure 15 we find changes in the range of up to -0.3 deg. Despite of these small values some trends may be evaluated requiring consideration of the corresponding chordwise pressure distributions provided in Figure 15a and 15b. For a better understanding of the results the positions of the flap tracks, the flap joint as well as fuselage diameter (dashed line) has been implemented in Figure 15. Note that the flap was attached to the fuselage by bolts near its leading edge. As the main wing shows little twist so close to the fuselage the visible change in twist is logically caused be the flap due to its loading. Figure 15a reflects the chordwise pressure distribution on the flap at about 18% wing span. Raising the model incidence (and, hence, the lift) causes a reduction of loading and, therefore, twist. Entering the post stall region (CL=2.2) further reduces loads. Considering the pressure distribution in the outer flap region at around 75% wing span we can’t recognize any flow separation. The maximum in wing plus flap twist appears for CL=1.9 at 60% span travelling inboard when increasing model incidence. This might be a consequence of the redistribution of flap loading due to the progressing inboard unloading.

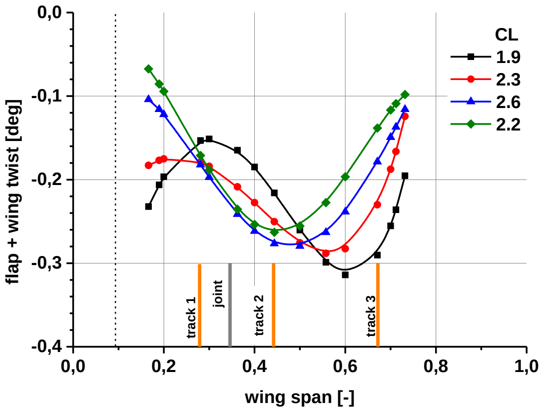

**Figure 15:** Flap twist measured by SPT 2

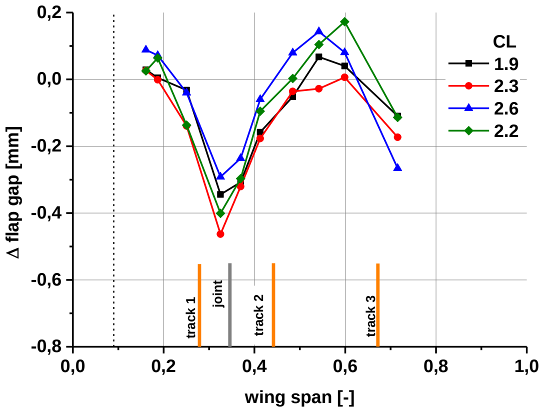

**Figure 16:** Flap gap assessment (SPT 2)

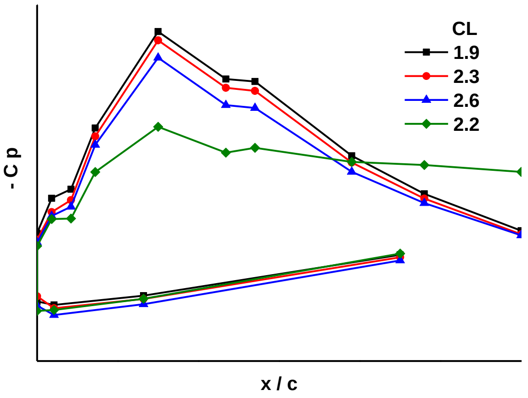

**Figure 15a:** Pressure distribution flap inboard

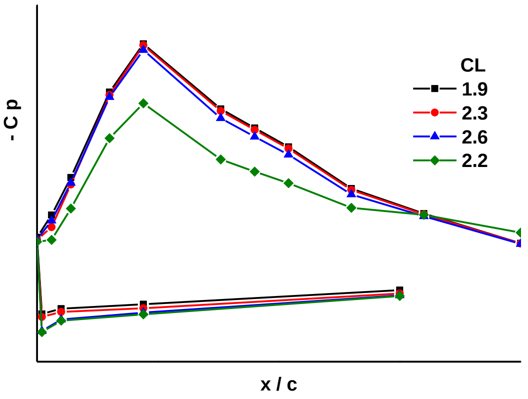

**Figure 15b:** Pressure distribution flap outboard

The flap gap assessment presented in Figure 16 is an outcome of the simultaneous monitoring by SPT 2 and 1. Based on tracking the marker shift on both elements the calculated change in flap gap is not the minimum distance between flap and main wing rather than the measured shift in position of flap and wing at the same chordwise location near the gap. Nevertheless, the achieved results allow for an understanding of the relevant behaviour in this region of the model. When looking at Figure 16 it should be kept in mind that the quoted accuracy of the SPT system is around ±0.05deg in twist. No lift effect is to be stated but gap maxima always appear at the middle between two flap tracks fixing the flap e.g. at x/c of 0.18 and 0.57. As the joint (realsied by dowel pins) between two flap elements at x/c =34% cannot transfer any bending it results in a maximum gap change due to the bending of the adjacent flap portions.

Deformation measurements on the Krueger flap were performed using the new high resolution SPT system no. 3. With reference to Figure 10 the tight arrangement of supporting bracket can be identified. Their spanwise position as well as the location of joints between different Krueger elements are indicated in Figure 17. We can clearly identify a gap increase with raising angle of attack. Furthermore increasing gaps are detected in the middle of larger spacings e.g. between track 2 and 3, 5 an 6 as well as 8 and 9. As the joints are unable transferring bending, minima in gap change are found at their locations.

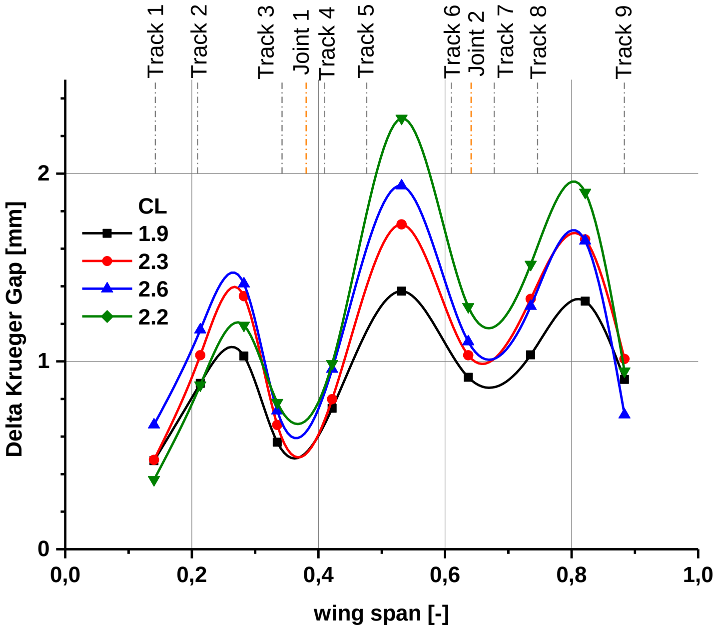

**Figure 17:** Observed gap change on the Krueger Flaps (SPT3)

It may be concluded that all three SPT systems provide plausible results and trends by a simultaneous provision of high resolution and measurement accuracy. Upgrading SPT 1 and 2 to the same capabilities in image resolution and acquisition rate as SPT 3 will allow for online measurements on multi-element wings. In the present set-up the viewing area of all systems covered the full span. Improvement with respect to accuracy may be gained when focussing on an inboard, central and outboard area with each system optimising the objectives. Such considerations are part of the ongoing system improvement activities at ETW.

## IV. Commissioning Dynamic SPT System

To enhance its test capabilities for future aeroelastic testing ETW procured a high-speed SPT system with a frame rate of 386 Hz for full image resolution going up to 1000 Hz by reducing the resolution. This allows the assessment of model vibrations and the resulting dynamic model deformation. To test and commissioning the new system several tests were performed to evaluate and quantify the operating limits and to investigate the handling of the system.

A first approach was using a shaking plate as wave generator excited by a conversion of a rotation into a translational movement (see Figure 18) provided only limited results. Due to high vibration levels of the complete setup and problems with overheated ball bearings, the maximum frequency was limited to 180 Hz. The results showed small deviations below 1.8% between the generated and the measured frequency, possibly caused by the measurement setup itself. Hence, to minimize the disturbing effects and also checkout higher frequencies another approach was necessary, resulting in the following test setup (see Figure 19).

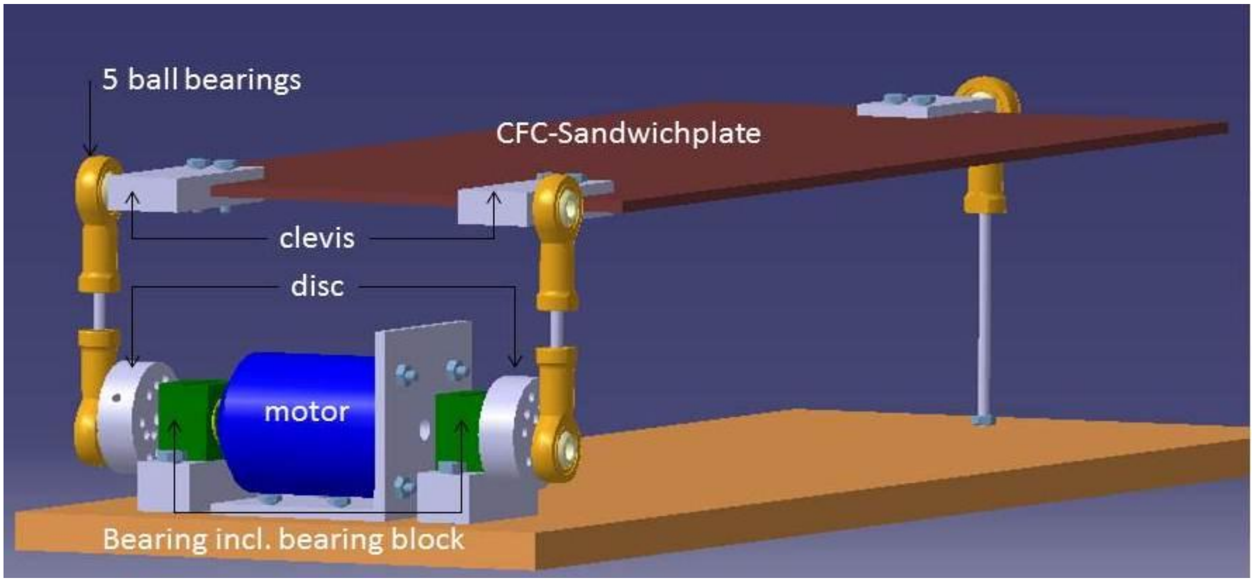

**Figure 18:** Model setup of the shaking plate

### A. Test Setup

With a possible image frequency of 1000 fps with a reduced image resolution, according the Nyquist-Shannon Theorem the maximal assessable model frequency is slightly less than 500 Hz. The reduced image resolution is reached by reducing the vertical sensor lines from 1728 lines to 664 lines while keeping the horizontal number of sensor lines constant, because the sensor reads the whole horizontal lines always completely.

An audio subwoofer was selected as test object, suitable to create any frequency within the requested range between 50 Hz to 500 Hz. The input frequency signal was created by a central clock generator, controlling a sine wave generator and amplified by a standard audio amplifier. The clock generator enables the synchronization between the created signal and the SPT image capturing. Figure 19 shows the schematic of the test setup.

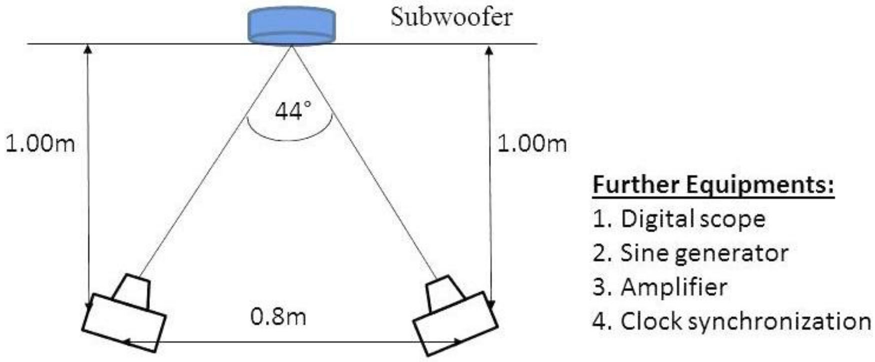

**Figure 19:** Measurement setup of the Subwoofer

## B. Results

From the several performed measurements the paper will concentrate on three different frequencies spread over the complete frequency range:

| Measurement | Frequency [Hz] |
|---|---|
| 1 | 50 |
| 2 | 400 |
| 3 | 495 |

**Table 2:** Measurement procedure

To get the best possible reference data, they are directly taken after leaving the audio amplifier. The evaluation of the reference frequency was straight forward, while the analysis of the SPT data was done by a FFT (Fast Fourier Transformation) analysis of the marker Z-coordinates. The FFT should directly indicate the frequency of the membrane oscillation. The FFT used a standard Hamming window with a quantity of $2^N = 1024$ sampling points (almost equal to the adjusted camera frame rate and suitable for a mathematical FFT).

The lowest frequency was acquired with the full image resolution of 2320 x 1728 and with the reduced resolution of 2320 x 664 to investigate the differences between high and lower image resolution. The comparison showed no significant differences between the two test cases.

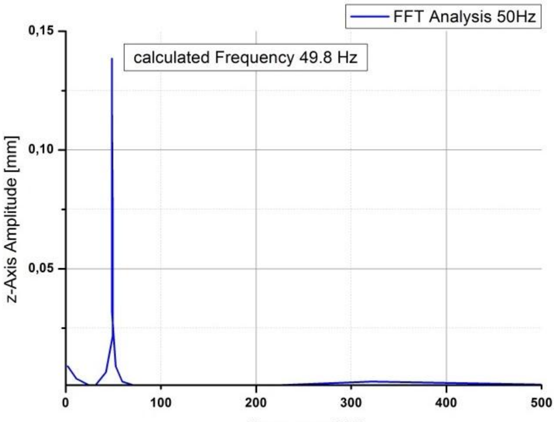

**Figure 20:** Measured frequency of the SPT-System

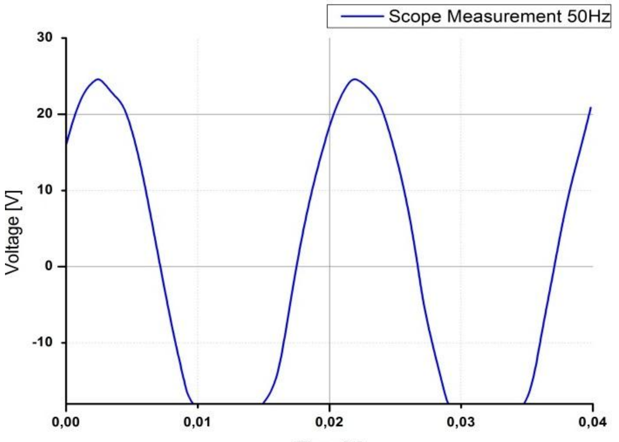

**Figure 21:** Appointed and amplified 50 Hz frequency

The measured frequencies deviate from the appointed and amplified frequency only by 0.2Hz, meaning only 0.4% measurement error. Within those results it has to be mentioned that the amplified sine wave is not perfectly shaped as expected. On top of the signal there is a little collapse of the amplitude which might cause the little frequency shift on the membrane deformation of the subwoofer. Even if this is not the cause of the error it can be stated that the subwoofer test setup showed at similar frequencies much smaller deviations, than the initial plate setup.

For the two higher frequencies the image was narrowed to 2320 x 664 Pixel to reach the maximum frame rate of 1000 fps. The scope measurement shows a value of 400Hz (see Figure 22 and 23). This frequency pointed out the disadvantages of this measurement setup. On one side high amplitudes of the membrane are required to allow the SPT system the measurement, on the other side the amplifier cannot enforce the unlimited amplitudes because of clipping. If clipping appears the FFT would not get the correct frequency from the SPT-data. After several trials a good compromise for the amplitude could be achieved. Analyzing the results showed a very low deviation between the generated and measured frequency of 0.02%.

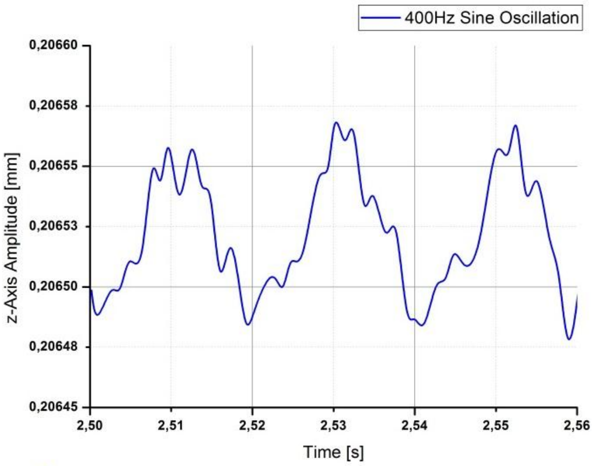

**Figure 22:** 400 Hz Sine Oscillation

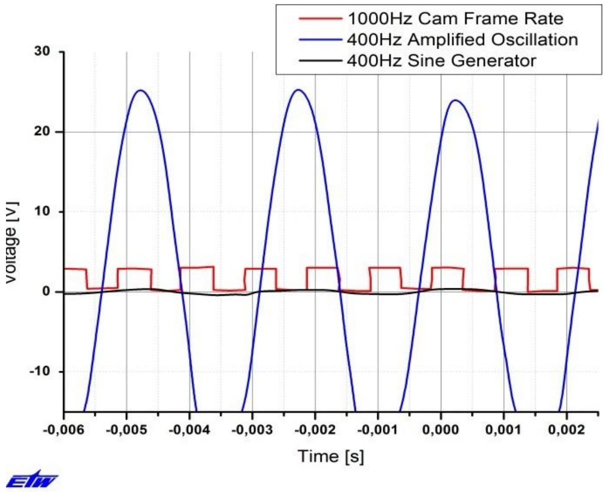

**Figure 23:** Representation of all measurement signals

Even at the highest frequency of 495 Hz the deviation was below 0.05%, so that the tests have proven the functionality of the SPT system up to the nominal reasonable oscillation frequency of 500 Hz. Mentionable is also, that during all measurements the 50 Hz net frequency influencing the subwoofer membrane was also optically detectable by the SPT system.

## V. Conclusion

The European Transonic Windtunnel has the capability to separate Reynolds-number, Mach-number and dynamic pressure (load) effects by varying the tunnel conditions. Hence the model geometry is an important variable for understanding of test results. Actually ETW has three model deformation measurement systems based on Stereo pattern tracking in operation. A fourth high speed SPT system capable for aeroelastic testing is in a commissioning state.

The paper gives an overview of the measurement principle, the setup and the usage of the Stereo Pattern Tracking Systems at the ETW. The enhancements during the last years allow the simultaneous use of three SPT-systems looking on different model components. Using improved camera hardware with increased image resolution and frame rates, the step towards continuously SPT sweeps seems also be feasible in the near future.

The newest high speed SPT-system should go even a step beyond measuring model oscillation frequencies up to 500 Hz. The described commissioning test using a subwoofer membrane validates the systems capability of accurately measuring high frequencies. The next steps are now the adaptation of the data reduction chain for high speed deformation data and the final commissioning test under cryogenic conditions in ETW test section.

Hence, ETW is able to cover most of clients' request for model deformation assessment under cryogenic and pressurized conditions, varying from standard tests over special applications like gap measurements to high speed aeroelastic test cases.

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