The Development and Application of Optical Measurement Techniques for High Reynolds Number Testing in Cryogenic Environment

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The European Transonic Windtunnel (ETW) is a pressurised cryogenic facility suitable to achieve flight conditions for cruise and high lift configurations of aircraft models. Becoming involved in the design process of new aircrafts or providing high quality data for the validation of CFD codes requires the availability of qualified measurement techniques for flow field analysis and model surface diagnostics.

Over the past decade ETW has developed special instrumentation and installations, together with optical methods for flow visualization or model deformation measurements in order to fulfil the requirements of high Reynolds number aerodynamic testing.

This paper gives an overview on the relevant optical tools operated under severe test conditions and presents new techniques under development. Gained experiences are addressed and achievements and maturity are documented.

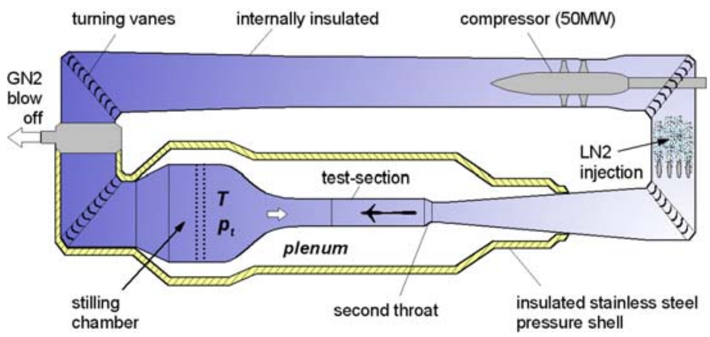

Figure 1. General view of the ETW aerodynamic circuit

List of Abbreviations

BOS	Background Oriented Schlieren
DGV	Doppler Global Velocimetry
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
IPCT	Image Pattern Correlation Technique
LLS	Laser Light Sheet
MDMS	Model Deformation Measurement System
PETW	Pilot ETW (ETW windtunnel at scale 1:8.8)
PIV	Particle Image Velocimetry
PSP	Pressure Sensitive Paint
SPT	Stereo Pattern Tracking
TSP	Temperature Sensitive Paint

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I. Introduction

The European Transonic Windtunnel is a high Reynolds Number windtunnel suitable for flight conditions testing on aircraft models. It is a continuous flow windtunnel with a working section of 2.0 m × 2.4 m and a Mach number range from 0.15 to 1.3. Flight Reynolds numbers can be achieved on full or half models by the use of cold and pressurised nitrogen. The facility operates within a temperature range of 312 K to 110 K and a pressure range from 125 kPa to 450 kPa.

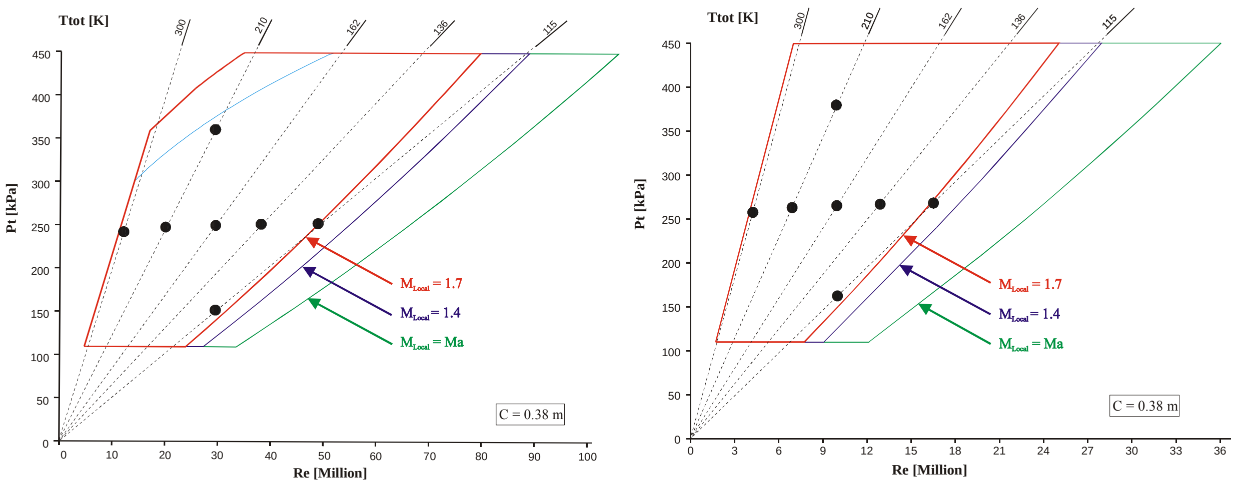

Figure 2. Test Envelopes for a Half Model at ETW at Mach 0.8 (left) and Mach 0.2 (right)

The proper adjustment of the total pressure and total temperature enables to analyze pure Reynolds number effects or pure aeroelastic effects. Pure Reynolds number effects are obtained by varying the temperature for a constant level of q/E (where E is the Young's modulus of the model material, which is temperature dependant) as shown on the envelopes of **Figure 2** with the horizontal lines. Pure aeroelastic effects are obtained at constant Reynolds number by a proper adjustment of total temperatures and total pressures as shown with the vertical lines of the envelopes of **Figure 2**.

These testing conditions enable realistic testing at flight Reynolds numbers and accurate evaluations of new aircrafts performances. Under these extreme conditions, it is essential to use appropriate and reliable measurement techniques, which can guarantee a high level of data quality. This document gives a short overview on the optical techniques available at ETW.

II. Transition detection methods

Two different optical methods for transition detection have been developed at ETW. Both are based on recording the temperature difference existing between the laminar and the turbulent regime of the boundary layer on a wing surface which undergoes transition. Since the adiabatic wall temperature difference across a transition line is estimated to be less than 0.5 K at transonic speeds, the temperature difference is artificially increased by introducing a quick temperature change into the flow, which will amplify the thermal signature across the transition.

A. Infra Red Technique

The first method, using the Infrared Imaging technique, can be proposed for temperatures between ambient and 220 K (with the AGEMA-Thermovision camera). The Infrared camera is installed behind a germanium window of a test section wall. The surface of this window is treated against reflections, and the model covered with white paint to avoid thermal disturbances and provide an insulation layer between the flow and the model structure.

Figure 3 shows an image obtained on a full model with the Infrared technique.

In order to amplify the thermal signature across transition lines, the temperature difference between the laminar and the turbulent parts of the boundary layer is artificially increased. This is done by introducing a quick temperature change into the tunnel flow (positive or

Figure 3. Example of transition detection with the infrared imaging technique on a full model

negative temperature step). Since the convective heat transfer coefficient is much higher in the turbulent part than in the laminar part of the flow, a temperature change in the outer flow is transferred faster to the wing surface adjacent to the turbulent region. The transition line can be seen as the borderline between light and dark areas in the Infrared image (**Figure 3**).

In cryogenic testing, IR imaging becomes more difficult because of the reduction in radiated energy and the shift to longer wavelengths. The working range of the AGEMA cameras used at ETW is limited to temperatures from 310 K down to 220 K. In former times, a special designed Infrared device (CRYSTAL camera) was used to cover also the lower temperature range (200 K to 100 K). Since it had to be operated using a sophisticated helium cooling cycle, it is very difficult to handle. Moreover, it was applicable to full model tests only. Since an alternative method of transition detection was developed for this temperature range as explained in the next paragraph, the CRYSTAL camera is no longer used at ETW.

B. Temperature Sensitive Paint

A second transition detection method, developed by DLR in cooperation with the Japanese Aerospace Research Institute (JAXA, former NAL), consists in a Temperature Sensitive Paint (TSP)[1]. This paint contains a luminescent material (luminophore) within the binder. Once excited with a light source, the luminophore reemits some light at longer wavelengths (fluorescence). The radiation intensity of the paint is temperature dependant. Thus, a picture of the temperature distribution on a profile gives information on the transition location currently for flow temperatures situated between 180 K and 110 K. This method can be used in addition to the Infrared technique to cover a large Reynolds number range. **Figure 4** describes the setup used for the technique. **Figure 5** give results obtained on the ETW reference model for four different Reynolds numbers (for details see Ref. 1). The transition detection line appears clearly, and the image resolution is better than with the infrared technique.

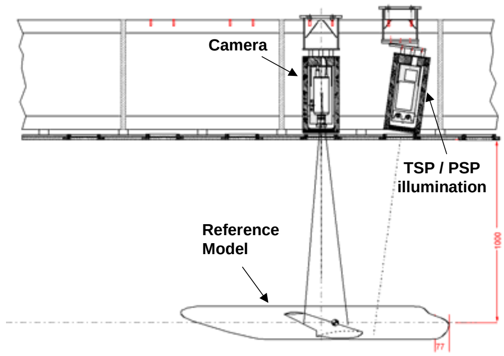

Figure 4. Test setup for TSP measurement on Full Model

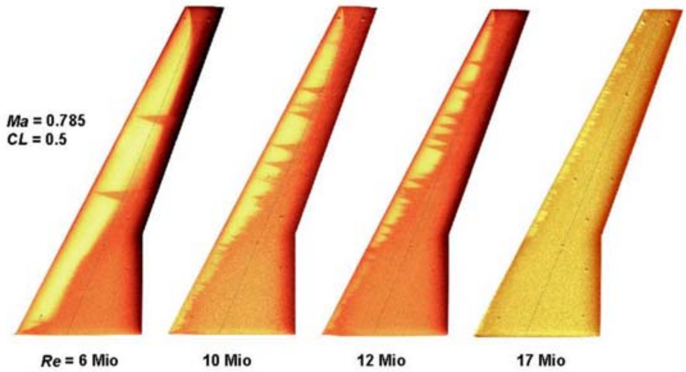

Figure 5. Example of transition detection with the TSP technique on the ETW reference model *(image released with courtesy of DLR)*

The method has been validated for temperatures below 200 K and Mach numbers down to 0.20, and has already been successfully applied on client models. For good quality image processing a temperature step with a gradient of dT/dt > 0.25 K/s should be performed, which can easily be achieved at high speed conditions by stopping the nitrogen injection (positive step), or by increasing it to a certain amount (negative step), whereas the former tunnel control only allowed to generate a negative step (forced injection) in the order of 0.2 K/s at low speed. The positive temperature step at low speed was not fast enough to produce images of sufficient quality during the first trials.

Hence, the success of TSP use at low speed conditions was limited. Since a temperature increase in the tunnel is generated by the compressor only, positive temperature steps with large gradients can not be generated at low speed. Consequently, it was decided to perform investigations in the PETW with 2-D profiles to determine the minimum temperature gradients needed to achieve good quality TSP images. This type of investigations have been performed in the ETW Pilot Windtunnel (PETW) at lower costs and with more flexibility.

Tests took place in October 2004 in the PETW to investigate the effect of thermal conductivity of the material on image quality and to clarify which cooling rate (0.2, 0.25, 0.3 K/s) is necessary to optimize the test conditions. The experience gained from these investigations led to a modification on the nitrogen injection system from ETW, allowing the achievement of suitable temperature steps and the acquisition of images of good quality.

III. Cryogenic Pressure Sensitive Paint

The conventional way of acquiring pressure measurements on a model is with a pressure-plotted model. Pressure taps can be machined on the model surface, then linked for the test to pressure sensors (PSI scanners installed in the model) by the mean of small tubes routed through the model. This method is well-known and widely used, however contains drawbacks: the pressure measurement is performed at discrete locations, the installation of pressure ports in a wing is a long and costly action, it limits the maximum wing load capacity and can therefore reduce the test envelope. For these reasons a Pressure Sensitive Paint, which can overcome these drawbacks, is of great interest.

The TSP was primarily tested at ETW in order to validate the setup (cameras and lights) for the major development of a Pressure Sensitive Paint (PSP) able to work under cryogenic conditions. In addition to the testing at low temperatures, the challenge of a cryogenic PSP lies in mastering the oxygen concentration in a windtunnel usually operating with nitrogen. First trials have been made together with DLR in the PETW in August 2004, followed by a test in ETW in October.

Both tests were carried out in cooperation with DLR and it was possible to handle the oxygen injection and measurement of oxygen concentration with the desired accuracy. At least, in both facilities an oxygen concentration between 500 and 2000 ppm could be achieved and held constant to ± 5ppm during PSP image aquisition. This is sufficient for doing PSP measurement under cryogenic conditions. So these first trials looked promising, and future developments performed by DLR will concentrate on increasing the sensitivity of the paint.

Figure 6 shows an image obtained with a pressure-plotted 2-D profile from DLR tested in the PETW. Two small cylinders were placed on the surface in order to create three-dimensional disturbances, whose effects on the pressure distribution are visible on the image. The picture shows as well the position of the shock at about 70% of the chord. These first trials look promising, and future developments performed by DLR will concentrate on increasing the accuracy of the cryogenic PSP technique. Although the cryogenic PSP has not yet reached a sufficient level of maturity for immediate use in client testing, this first step clearly indicates the potential of this new technique for the future and has demonstrated the operability of the oxygen injectionconcept, a mandatory requirement for the application of PSP.

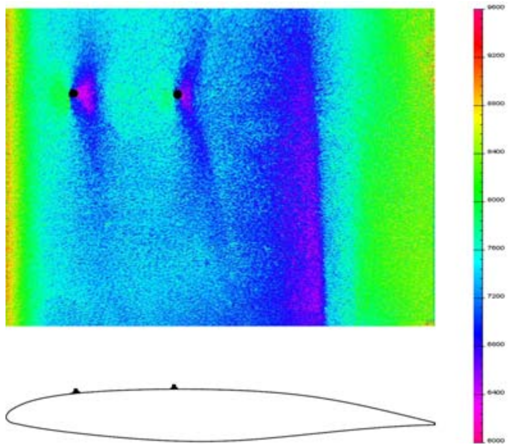

Figure 6. Image obtained with the PSP technique on a 2D profile tested in the PETW *(image released with courtesy of DLR)*
T = 230 K, Pt = 120 kPa, Ma=0.79

IV. Model Deformation Measurement

When it turned out that the metallic windtunnel models are not perfectly rigid, the accurate determination of wing twist and bending has become of major importance in windtunnel testing. The capabilities of the European Transonic Windtunnel to independently vary pressure and temperature enable to separate pure aeroelastic effects from pure Reynolds number effects (see **Figure 2**), thus allowing a better understanding of the aerodynamic and aeroelastic phenomena.

Figure 7 illustrates the importance of separating both effects. The centre part of the figure shows the behavior of the pitching moment characteristics for three different test conditions, obtained by varying the total pressure at

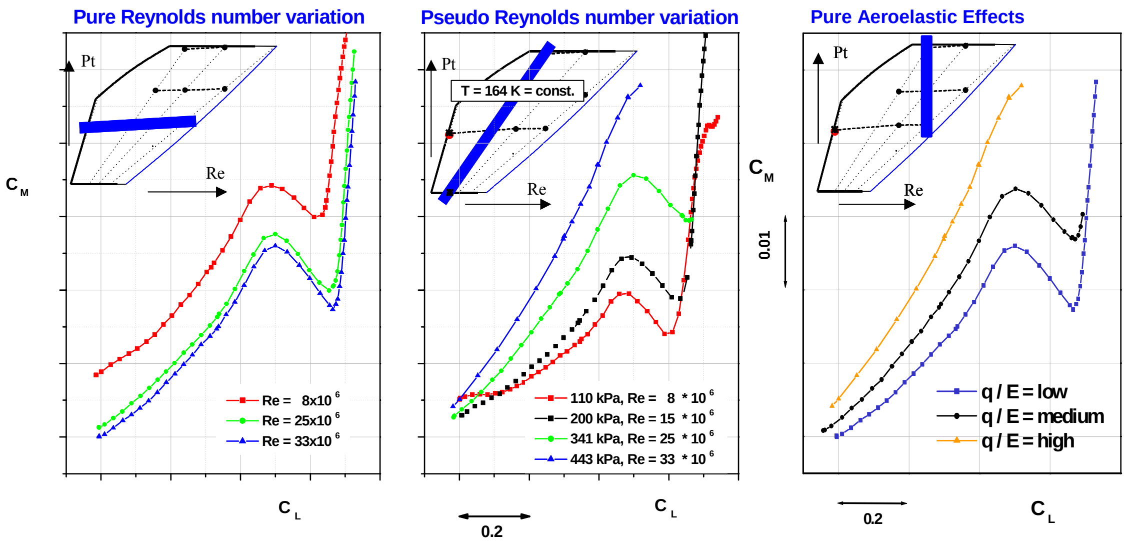

Figure 7. Pitching Moment / Lift characteristics *(at Mach 0.85)*
Pure-Reynolds number effects, pseudo Reynolds number effects and pure aeroelastic effects

constant total temperature. The results show pseudo-Reynolds number effects, since the Reynolds number and the aeroelastic effects are mixed. The next two plots show pure Reynolds number effects (left) and pure aeroelastic effects (right) on the pitching moment. These three plots show clearly that Reynolds number effects can not be correctly evaluated if the Reynolds number is varied by increasing pressure at constant temperature. The dominating effect in this case is the aeroelastic effect.

The aerodynamicists request the exact wing geometry to perform correct analyses and comparisons with the experiment. It is an essential issue for the validation of CFD codes. By modifying the dynamic pressure level at constant Reynolds number, not only can the jig shape of the wing be matched, but also a large range of wing twist and bending cases can be produced. Therefore, a wing deformation measurement system at ETW with high accuracy is essential to enable a complete analysis and understanding of test data.

ETW has made many efforts to develop accurate model deformation measurement techniques for half and full models. In addition to the MDMS (Model Deformation Measurement System) established with DLR, three techniques have been developed at ETW as described in this chapter.

A. Model Deformation Measurement System (MDMS)

The first measurement technique was developed in collaboration with DLR. The application is limited to full models at ETW, as the system can only be installed in the top wall of the test section. This non-intrusive method is based on the Moiré fringes technique.[2]

The technique consists in projecting a grid of black lines onto the wing. The Moiré pattern is observed through a second grid (reference ruling) and is transformed into relative heights of the wing surface by 2-dimensional FFT. The resulting fringes in the Moiré interferogram represent lines of equal elevation (**Figure 8**). Absolute heights are obtained by means of a laser-generated spot on the wing which is needed to correct for optical effects.

Although described as non-intrusive, the method requires coating of the wing with white, non-reflecting paint with careful grinding to obtain a smooth surface. The deformation measurement covers the full surface of the wing, but can only be performed on profiles without components like flap track fairings, nacelles, etc… The image processing is relatively complex and requires substantial, time-consuming post-processing, hence the method is available with restrictions.

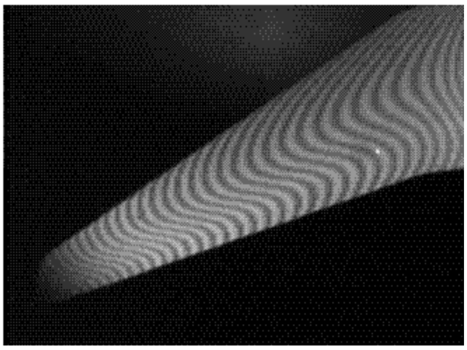

Figure 8. Moiré interferogram on a full model wing

B. Wing Pressure Evaluation

Initially thought of as a cross-checking tool for MDMS measurements, the wing pressure evaluation method has evolved into an acknowledged twist determination technique. Although the method does not rely on an optical hardware, it is briefly described in this paper as it belongs to a verification method for the optical methods and contributes to the gaining of confidence of the deformation measurement techniques.

The basic ideas of the method [3] are the following:

- Each pressure tap on a wing showing a distinct pressure variation with α (angle of incidence) is regarded as a differential incidence meter.
- The local incidence angle at a given wing section differs from the global model angle of attack by the local twist angle.
- Comparing pressures acquired at the same Mach and Reynolds numbers, but different tunnel pressures, the effective local twist is determined as $\Delta\alpha_{eff} = f(C_L, q)$ for each measured wing section.
- Based on the wing planform and the spanwise distribution of the effective twist, the change of the induced downwash $\Delta\alpha_{induced}$ due to the twist itself is assessed.
- Geometric twist = Effective twist + $\Delta\alpha_{induced}$

This method can be used for any pressure-plotted wing and requires at least data at two, preferably three total pressure levels. A typical wing with 5 or more pressure rows gives very detailed information on the wing spanwise deformation. **Figure 9** illustrates the differences measured in local pressure on a wing tested at constant Reynolds number but different total pressure levels. **Figure 10** gives a comparison of the twist measurement of a full model wing from both the MDMS and the pressure derivation method. For four different C_L values we see a good agreement between both methods: the wing twist is determined with an accuracy of better than 0.1º.

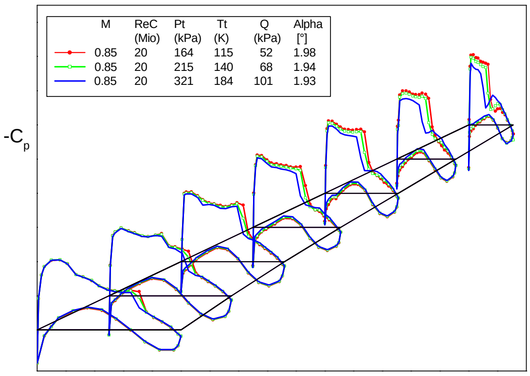

Figure 9. Dynamic pressure effect on wing pressure coefficient

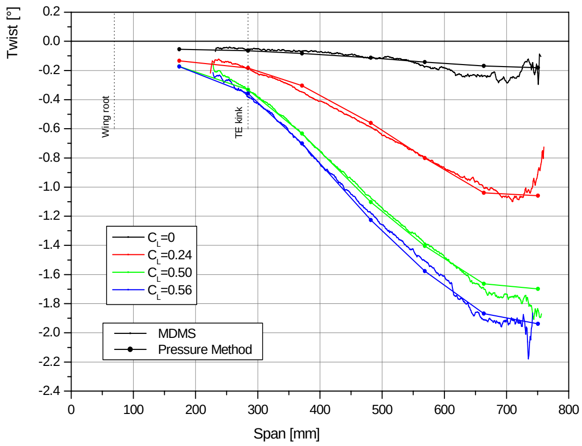

Figure 10. Full Model wing twist evaluation with MDMS and pressure method - *comparison*

C. Stereo Pattern Tracking (SPT)

Since the MDMS was adapted at ETW only to full models, and demands a complex processing, a new system was required for deformation measurement also adapted to half models. The basic principle of the SPT is rather simple, as is the setup itself. The post-processing of the images is performed automatically and on-line, which is an advantage with respect to the MDMS.

The optical system focuses on dots distributed on two lines along the leading edge and the trailing edge as shown in **Figure 11**. The markers are circular Letraset dots of 10 mm diameter (corresponding to approximately 15 pixels) with a thickness of 5 µm. The system requires a good contrast to the background which must not change with the model position. Since it is difficult to get rid of light reflections for all model positions and lighting conditions, the dots have previously been applied on a thin paint layer as shown on **Figure 11** (total thickness with paint: 20 µm). New Letraset markers (white ring around a black dot) have recently improved the situation and avoided the application of paint, which decreases the model preparation time and reduces the impact of the dots on the flow to minimum.

Figure 11. Half Model Wing fitted with SPT markers

Two cameras installed in the sidewall look at the entire wing surface with two different viewing angles. By processing these images the SPT system can compute the 3D coordinates of up to 40 markers. The density of the dots increases towards the wing tip to compensate the shortening of the wing chord, and thus still guarantee a good accuracy around this region.

The position of the cameras needs to be calibrated. This is performed with a special frame, on which about 30 bulbs are installed. The frame is installed together with the model in the test section. The relative coordinates of each bulb is known exactly by measurement in the workshop (with an accuracy of better than 0.1 mm). The bulbs are sequentially switched on, automatically identified by the SPT and linked to their 3D coordinates. The position of the frame relative to the tunnel or to the model is not relevant.

The SPT system determines the model marker coordinates in the model system. Reference images are taken wind off while pitching the model through an adequate alpha-range. Marker positions in the Model system are determined prior to each run with new reference images to compensate for effects caused by changes of temperature and gas density. The markers are moving on circles around the axis of rotation, which is determined by a non-linear least square fit. For each marker the centre, radius and angular offset are determined. The position of one reference marker is manually measured in model coordinates to define the offset between SPT and Model system. A software package has been developed to transform these coordinates into twist and bending.

The SPT system delivers coordinates continuously with a rate of 7 Hz (shutter speed of 2/100 s). Productive data are measured in pitch/pause mode, with approximately 3 s (i.e. 21 exposures for each model position). Coordinates marked as "doubtful" by the SPT or outliers are dropped automatically. Raw coordinates show a scatter of about 0.5 mm, and averaged coordinates at one alpha-position typically have a standard deviation of about 0.2 mm. Raw images can be stored on disk, but this reduces the data transfer rate for coordinates to 1Hz.

Images can be stored for documentation, but this is not required for the determination of twist and bending (which saves a lot of disk space).

D. Image Pattern Correlation Technique (IPCT)

The model deformation measurement technique IPCT uses a combination of photogrammetry algorithms and the cross correlation algorithms developed for Particle Image Velocimetry (PIV).

The IPCT technique was used for the first time at ETW end of 2003 by DLR. It was used on a Half Model to estimate the wing deflection by observation of the wing tip. The wing tip fence of the model was coated with a black layer of paint, on top of which a random speckle of white dots was created (**Figure 12**). A CCS camera was fixed below the bottom wall of the test section in order to record images of the wing tip at the different positions during the test. These wind-on images were later compared to the reference wind-off images, and a software developed by DLR converted the displacement of the dots into twist and bending information.

Figure 12. IPCT Speckle

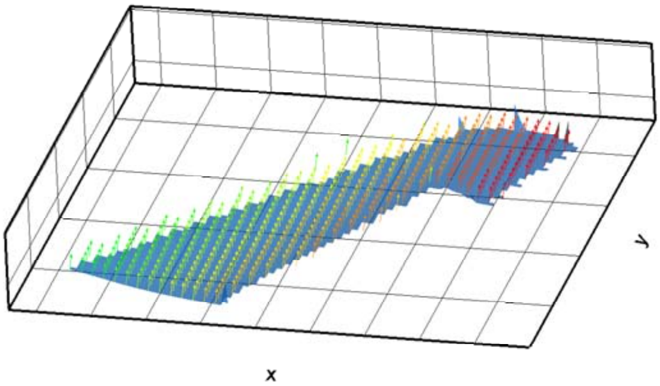

Figure 13. 3D deformation vector field plotted over the reference wing surface, vector magnitude is colored coded
Image released with courtesy of DLR

More recently the same technique was tested on a similar model, this time with a coating on most of the wing lower surface. **Figure 13** shows the results of the displacement vector-field computed from IPCT images of the Half Model wing. The system was used in parallel to the SPT measurements. SPT dots were applied on top of the wing lower side coating and both techniques were tested simultaneously. However, at the time of publication no comparison has been made between both techniques.

IV. Wake Vortex Visualisation Techniques

A. Doppler Global Velocimetry (DGV) [4,5]

Doppler Global Velocimetry is a non-intrusive technique which provides planar velocity data through the imaging of light-sheet illuminated particles suspended in the flow. DGV relies on the indirect measurement of the frequency shift of light scattered by the particles. A single camera imaging a single light sheet can only provide a single velocity component. Measurement of all three velocity components requires a combination of multiple viewing positions or multiple (coplanar) light sheet directions. However, due to the constraints associated with the ETW facility (limited space and optical access, low temperatures, high aerodynamic loads), the ideal imaging arrangement as used for PIV measurements in conventional windtunnels was not feasible. Instead three cameras placed behind windows of the sidewalls of the test section obliquely viewed two coplanar light sheets spanning the test section (**Figure 14**).

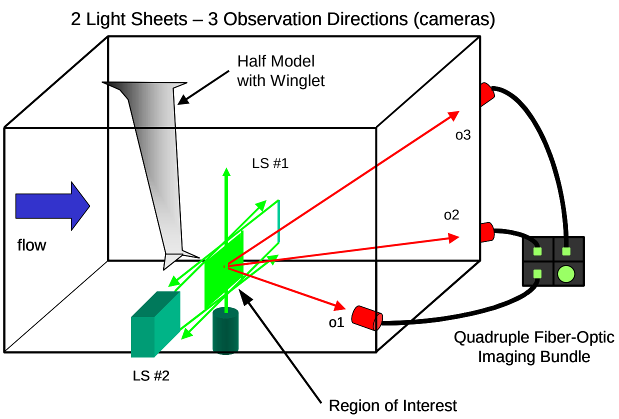

Figure 14. Doppler Global Velocimetry installation in ETW

A series of tests was conducted at low speed with active seeding in the framework of the M-DAW project[4,5]. **Figure 15** shows velocity vector fields behind the wing tip obtained with the DGV technique during this project.

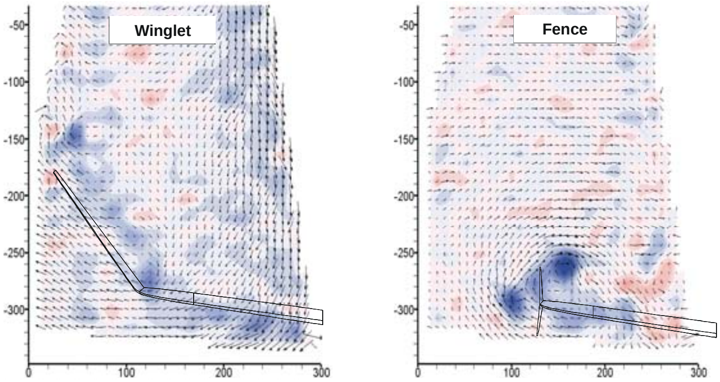

Figure 15. Velocity vectors in the wing tip area measured by DGV at cryogenic conditions

The choice for the seeding had to fulfill the requirements of ETW. It had to keep the tunnel clean and be easily removable after the test. Excluding the existing oils used in the conventional windtunnels for PIV measurements, the decision was made to use water. The seeding finally comprised in a stream of warm nitrogen mixed with water vapor which was injected into the ETW aerodynamic circuit downstream of the second throat. Once introduced into the flow the water vapor condenses into tiny ice crystals with a size of less than 1 micrometre. The continuous blow-off in the ETW results in a gradual decay in seeding density over time. This seeding method does not leave residue after the measurement apart from humidity, which will be automatically purged from the facility. For low speed tests (Mach 0.3), the seeding involved a continuous injection of about 1kg/s dry nitrogen mixed with saturated steam.

At low temperatures and after a long time testing with seeding, ice started to appear on windows. Eventually the visibility became insufficient for useful images to be acquired. This situation has recently been improved by window heating and purging concepts.

B. Laser Light Sheet (LLS)

The Laser Light Sheet technique was tried for the first time in November 2004 in cooperation with DLR. This non-intrusive technique was applied to a half model test in order to determine the position of the wake vortex at low speed in high lift configuration. The black spot visible on **Figure 16** corresponds to the centre of the wake vortex in a plane defined by laser illumination. As for DGV, the Laser Light Sheet technique uses seeding in the form of small ice particles. Two cameras fixed in the outer and the inner walls of the test section observe a light sheet generated by a single laser. The ice crystal particles visible in the flow give information on local flow density only, the technique does not give values of the local velocity.

Figure 16. Wake Vortex Centre observed with LLS technique

For this first trial two types of seeding were available: in addition to water vapor already used for DGV, small water droplets were injected in the flow with an aerosol. These droplets immediately freeze when entering the cold tunnel. Some experience was gained on seeding optimization (size and density) for both methods at diverse tunnel temperature and pressure conditions. Some icing problems on the windows remained at low temperatures. Developments on new types of seeding, are ongoing.

C. Background Oriented Schlieren (BOS)[6]

The BOS technique was first tried at ETW in November 2004 in cooperation with DLR (in parallel to the LLS technique). This technique was proven to be operational in laboratory tests for accurate qualitative visualization of the density gradients in a flow. The technique aims at observing the position of the wake vortex for various test conditions and model attitudes at low speed. The setup involved three cameras fixed in both sidewalls and in the top wall. Each camera is focused on a special speckle background fixed to the opposite tunnel wall (identical to the IPCT speckle, see **Figure 12**), and observes the displacements of the image. These displacements occur through light ray deviation due to variations in the local fluid densities. Displacements of the dots from the speckle background with respect to a reference wind-off image are correlated to flow density variations in the volume covered by the camera field of view. **Figure 17** shows a result obtained with this technique on a half model wake with the top wall camera. The colors and sizes of the arrows correspond to the density gradients observed in the considered

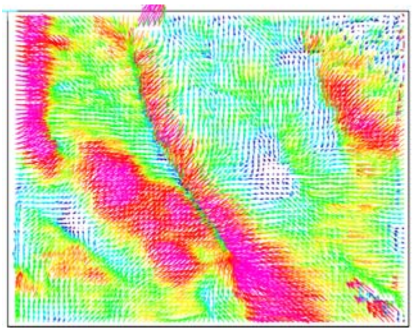

Figure 17. Half Model Wake Vortex Visualization with Background Oriented Schlieren technique.
View from top wall, pt=2.5 bar, Tt=210 K, M=0.2
(flow comes from the bottom of the image)

region. This image shows various effects since the camera observes the whole shear layer of the wing, but the wake vortex is clearly visible. The fields of view of the sidewall cameras intersect the one of the top wall camera, so that it is possible with proper cameras adjustments to localize precisely the centre of the vortex and evaluate the flow density around this region.

The BOS system works properly for wind tunnel applications, but the accuracy of the method for this first trial at cryogenic conditions was limited. However, a lot of experience was gained on the feasibility of the method. The technique has not come to maturity yet, but some improvements are already foreseen in order to increase the accuracy of the optical analysis.

V. Conclusion

The variety of the optical measurement techniques available or under investigation at ETW as described in this paper show that the European Transonic Windtunnel has turned into a mature windtunnel over the past years. The infra-red imaging and the TSP techniques are now well established, and can be used as complementary techniques. However the recently-developed TSP is still evolving, and could in the near future enlarge its working range to cover the full temperature range of ETW, and be used with a better accuracy on small model parts and at low speeds. The PSP technique has shown after the first trials mentioned in this paper a big potential for the future. It is hoped that improvements can be made by our partners on measurement accuracy and surface roughness quality, which currently does not match the specific requirements of flight Reynolds number testing. The SPT technique is nowadays used as an accurate and reliable non-intrusive deformation measurement technique both for half and full models. The first measurements with a full model were performed in November-December 2004 and have shown a very good agreement with the pressure-derivation method. Future developments will be made in order to measure the deformation of small model parts like flaps, which will require a dedicated set of cameras and a new calibration frame. The flexibility and relative simplicity of the method represents a very good alternative to the MDMS. Indeed, even if the accuracy of the MDMS has been proven, the SPT can be offered for both half and full models and can deliver real-time results during testing. The first two tests with the IPCT method, which were of increasing complexity, have shown that the method is still evolving towards a more accurate method. Due to the currently existing post-processing time and complexity, and the accuracy level, this method can be proposed for the moment as a verification method for model deformation measurement. However, further developments of the technique could bring it to a higher level of confidence in the future.

The DGV technique has produced relevant data during the M-DAW project and was proven to be working at cryogenic conditions. However, problems associated with seeding did limit the success of the technique at low temperatures. The first trials with the LLS technique used the first experiences gained with the M-DAW campaign, thus allowing a better mastering of the water vapor and aerosol seeding. Further improvements will be made with window heating and purging concepts, in parallel to further developments with seeding. Future developments will involve a possible enhanced setup with a more powerful laser allowing first trials with Particle Image Velocimetry measurements. In spite of successful trials in laboratory and conventional windtunnel testing, the BOS technique did not reach a sufficient level of accuracy for this first trial in a cryogenic windtunnel. It is hoped to improve the situation with the development of new cameras housings limiting the flow convection and unsteady temperature gradients between the window and the optics.

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