Advanced Measurement Techniques for High Reynolds Number Testing in Cryogenic Wind Tunnels

U. Fey[1], R. Konrath[2], T. Kirmse [3], T. Ahlefeldt[4], J. Kompenhans[5]
German Aerospace Center (DLR), 37073 Göttingen, Bunsenstrasse 10

Y. Egami[6]
now: *Nagoya University, Nagoya, Aichi-prefecture, 464-8603 JAPAN, Furo-cho, Chikusa-ku*

The present paper addresses the development, qualification trials and application of some non-intrusive measurement techniques suitable for operation in industry-scale, pressurised cryogenic wind tunnels. The application of cryogenic Temperature-Sensitive Paint (cryoTSP) as a tool for transition detection is described as well as the implementation of the Image Pattern Correlation Technique (IPCT) and the Backward Oriented Schlieren method (BOS) in the European Transonic Windtunnel (ETW). Progress on the development of cryogenic Pressure-Sensitive Paint (cryoPSP) is shown, and considerations for the establishment of a Particle Image Velocimetry system suited for low temperatures (cryoPIV) are presented. Furthermore, the state of adaptation of the microphone array technique (MAT) to industry-scale, cryogenic wind tunnels is described.

I. Introduction

FUTURE generations of aircraft will be developed by applying 'High Reynolds Number Design', using advanced computational aerodynamics and industry-scale cryogenic wind tunnels which enable aerodynamic optimization tests for flight Reynolds numbers on a scaled model. For validation purposes and to further improve the computational techniques, accurate aerodynamic field data such as transition location, surface pressure distributions, velocity fields, shock locations or flow separation must be supplied during the design process. Thus, modern measurement techniques commonly used in (warm) industrial wind tunnels have to be made available for application to cryogenic wind tunnels as well.

Flight Reynolds number testing on scaled aircraft models is presently in use only in the European Transonic Windtunnel (ETW) in Germany and in the National Transonic Facility (NTF) in the US. Both facilities adopt the same concept regarding the generation of the relevant test conditions by using moderately compressed pure nitrogen at cryogenic temperatures as the test gas. During the last decade the achieved benefits of this simulation technique could be impressively demonstrated, leading to modifications of modern aircraft design chains brought about by a fruitful cooperative application of numerical design tools and wind tunnel testing. As an outcome of this symbiosis, customers expressed an additional need for information to be gathered by advanced techniques such as are commonly used in 'warm' transonic wind tunnels. Ideally, all applied techniques should be non-intrusive, especially when paying due regard to the thin boundary layers on model surfaces at high Reynolds numbers.

The DLR Institute of Aerodynamics and Flow Technology develops and has operated over many years a multitude of non-intrusive (mostly image-based) measurement techniques in 'warm' industry-scale wind tunnels. Based on today's demands to implement these measurement techniques also in cryogenic wind tunnels, especially in the ETW, some projects have been started to address this subject. The progress and the status of cryogenic measurement technique development at the Institute are presented in this paper.

---

[1] Research Scientist, Inst. of Aerodynamics and Flow Technology, uwe.fey@dlr.de
[2] Research Engineer, Inst. of Aerodynamics and Flow Technology, robert.konrath@dlr.de
[3] Research Engineer, Inst. of Aerodynamics and Flow Technology, tania.kirmse@dlr.de.
[4] Research Engineer, Inst. of Aerodynamics and Flow Technology, thomas.ahlefeldt@dlr.de
[5] Head Experimental Methods, Inst. of Aerodynamics and Flow Technology, juergen.kompenhans@dlr.de
[6] Assistant Professor, Grad. School of Micro-Nano Sytem Engineering, y.egami@coe.mech.nagoya-u.ac.jp

II. Measurement Techniques

A. Cryogenic Temperature-Sensitive Paint (CryoTSP)

With respect to a future ‘green’ aircraft, Natural Laminar Flow (NLF) and Hybrid Laminar Flow Control (HLFC) are favoured techniques with a potential for further reduction of aerodynamic drag. Optimization of NLF and HLFC in ETW and improvement of the computational prediction methods require experimental techniques to determine a wind tunnel model’s boundary layer state under cryogenic conditions. Since the application of the IR technique is limited to temperatures above 200 K, an alternative method has been found with cryoTSP, which is based on the thermal quenching of molecules embedded in a paint layer. CryoTSP can be applied using a spray gun, and surface quality with a high degree of smoothness can be obtained by polishing (Fig.1).

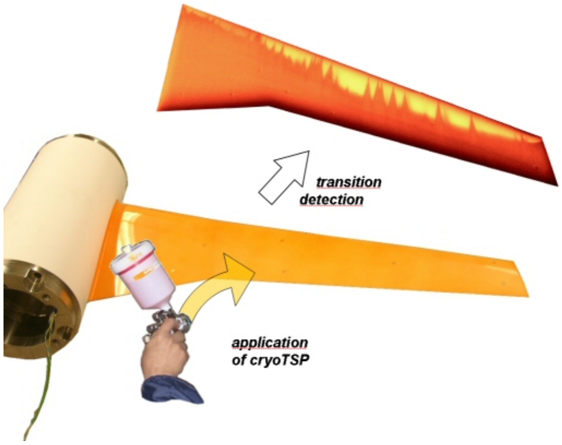

Figure 1. Application of cryoTSP to a cryogenic wind tunnel model used for transition detection measurement.

With the help of the cryoTSP technique, the laminar-to-turbulent boundary layer transition on wind tunnel models can be detected, as well as the location of shocks, footprints of vortices or flow separation.

Transition detection using cryoTSP has been successfully applied by the Institute of Aerodynamics and Flow Technology at the ETW wind tunnel since the beginning of 2003[1], initially in close cooperation with the Japanese Aerospace Exploration Agency (JAXA, formerly NAL). The original cryoTSP paint was optimized for large, industry-scale wind tunnels like ETW by JAXA. Within the last years, the PSP/TSP group of the Institute of Aerodynamics and Flow Technology has continuously improved the cryoTSP technique in cooperation with ETW and new paints have been designed to extend the application range of the Temperature-Sensitive Paint method.

For example, a two-component cryogenic TSP (2C-cryoTSP) was developed to cover the complete temperature range given in cryogenic wind tunnel testing (110 K < T < 300 K), requiring just a single coating application, and using excitation light at two different wavelengths[2]. Before this new 2C-cryoTSP had been available, the TSP paint for cryogenic wind tunnel testing ‘only’ covered the temperature range 110 < T < 220 K. Transition detection for T > 220 K had to be done by the use of an additional IR camera. Hence, depending on whether the wind tunnel temperature was above or below 220 K, the data acquisition method had to be changed accordingly. Furthermore, an IR camera gives less spatial image resolution compared with the modern, high-resolution (b/w) CCD cameras used to capture the cryoTSP images.

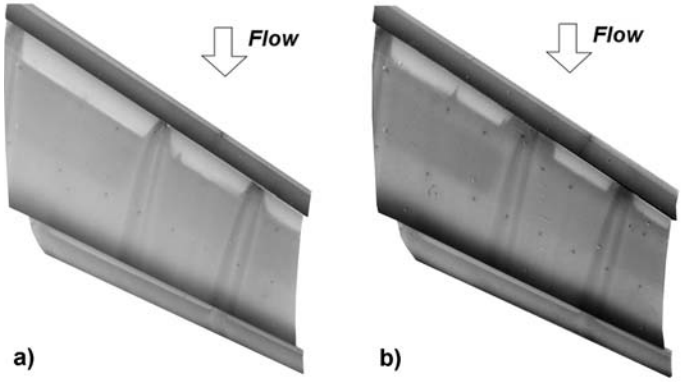

Figure 2. 2C-cryoTSP result images of a section of a half model wing tested in ETW. a) T = 300K, Re = 2.3 Mio, ‘warm’ component of TSP was used. b) T = 160 K, Re = 5.4 Mio, cryogenic component of TSP was used

Meanwhile, the cryoTSP technique has become the major tool for laminar flow investigations in cryogenic wind tunnels and the technique has been operated successfully in the ETW, the pilot-facility of the ETW (PETW), the cryogenic wind tunnel of the German-Dutch Windtunnels in Cologne (DNW-KKK), and the cryogenic Ludwieg Tube facility in Göttingen (DNW-KRG). Figure 2 shows transition images captured under warm and cold conditions in the ETW cryogenic wind tunnel using the 2C-cryoTSP.

B. Cryogenic Pressure-Sensitive Paint (CryoPSP)

The conventional way of acquiring surface pressures in wind tunnel testing is by using test models equipped with pressure taps. This method is well-known and widely used but has inherent drawbacks: the pressure measurement is performed at discrete locations, the installation of pressure taps in a wing is a long and costly process which can limit the maximum wing load capacity and therefore reduce the test envelope. Hence, Pressure-Sensitive Paint (PSP), which can overcome these drawbacks, is of great interest.

However, the application of PSP in cryogenic wind tunnels is not straightforward since the test conditions there are quite different from those of conventional ‘warm’ wind tunnels[3]. Cryogenic wind tunnels use evaporated liquid nitrogen as a test gas to decrease the tunnel temperature. PSP, on the other hand, needs oxygen because the working principle is based on ‘oxygen quenching’.

Thus, conventional PSP as commonly used in a ‘warm’ wind tunnel (operating gas: air = 21% oxygen) is not suitable for cryogenic testing. However, some oxygen needs to be added artificially in a cryogenic wind tunnel. The possible amount of oxygen injection in the (large) ETW wind tunnel is limited; if, for example, only one percent of oxygen were to be added to the flow in high Reynolds number testing (i.e. high Mach numbers and high flow rate), this would require large plants and oxygen vessels, resulting in a considerable safety risk.

The reason is that ETW during operation needs to continuously inject liquid nitrogen at up to 250 kg/s in order to maintain the flow temperature, thus compensating the heat input of the compressor (50 MW), and the evaporated, gaseous nitrogen has to be exhausted continuously to maintain constant pressure. Therefore, artificially added oxygen cannot accumulate and if one needs high oxygen concentrations it is necessary to inject it continuously at a high rate. In consequence, the possible oxygen concentration suitable for cryoPSP testing in ETW in practice is limited to about 500 – 5000 ppm (0.05 – 0.5%).

Furthermore, the binder of a Pressure-Sensitive Paint has to be oxygen permeable since PSP basically is an oxygen partial pressure sensor. Conventional binders suitable for PSP therefore have a more or less rough surface, and a silicon-based binder such as is used in the DLR-02 PSP-paint, for example, loses its permeability at low temperatures. Hence, the challenge in cryoPSP design is to find a pressure-sensitive molecule which is sensitive enough to deliver high signal-to-noise ratio measurements at the low oxygen concentrations, and a cryo-proven binder which exhibits adequate oxygen permeability along with sufficiently high surface quality and smoothness.

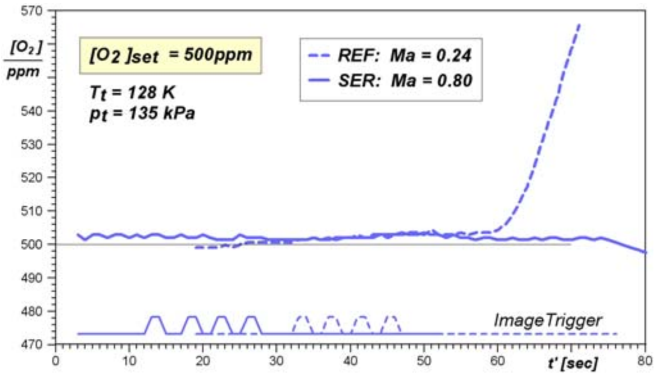

Figure 3. Time series of oxygen concentration during cryoPSP data acquisition in ETW. Dashed lines: during acquisition of reference images, solid lines: during acquisition of pressure distribution images.

From the point of view of the wind tunnel, the challenge is to implement an oxygen injection system able to generate the desired oxygen concentration and to hold it constant during PSP image acquisition (otherwise cryoPSP results would reflect oxygen concentration changes rather then pressure variations).

First trials with cryoPSP were made in the PETW in August 2004, followed by a test in ETW in October of that year. Oxygen injection with homogeneous distribution and with a measurement of its concentration with the desired accuracy could be achieved in both tunnels: here an oxygen concentration between 500 and 2000 ppm could be established and kept constant to ± 5ppm during the acquisition of PSP images (see Fig. 3).

In 2005, a cryoPSP test was successfully performed also in the cryogenic (blow-down) Ludwieg tube facility DNW-KRG. These first results obtained in the three wind tunnels were very promising and showed good *relative* pressure distributions. However, signal-to-noise ratios are lower than with ‘warm’ PSP results and the determination of *absolute* pressure values is much more difficult. Therefore, cryoPSP needs further improvements; these are under development at the Institute of Aerodynamics and Flow Technology, in co-operation with the ETW wind tunnel group.

C. Cryogenic Particle Image Velocimetry (CryoPIV)

Particle Image Velocimetry (PIV) is a widely-used and well-developed non-intrusive measurement technique to determine unsteady as well as time averaged velocity vector fields inside a slice of the flow field[4]. For PIV measurements, the flow is seeded with small flow tracers. Using high energy pulse lasers, a thin light sheet illuminates the measurement plane in the flow. The light scattered by the particles inside the light sheet is recorded by specific cameras. Digital correlation analysis is applied to successively recorded images to determine the local particle shifts, from which the velocity vectors are calculated. Flow separations at rudders or flaps, for example, or the generation of vortices at interfaces and flow control devices can be visualized and their interaction with the flow on the wing can be investigated quantitatively. The possibility to apply PIV in cryogenic facilities like the ETW is of particular interest since this would make available detailed information from the flow field at flight Reynolds and Mach numbers.

The main problems occurring for the adaptation of this technique to cryogenic conditions are the generation of suitable tracer particles, the realization of optical access for a high energy laser light beam to the test section and the compensation of light deflections due to pressure and temperature gradients in the flow.

At transonic speeds flow tracers of the order of 1 µm are usually small enough so that the lag between the motion of the tracers and the flow can be neglected. Moderate tracer concentrations in the flow are necessary to get a good spatial resolution of the measured velocity field. Figure 4 shows the result of a Stereo-PIV measurement in the cryogenic low-speed wind tunnel DNW-KKK at a flow temperature of 150 K ($R_{mac} = 6$ Mio). This wind tunnel was used for preliminary studies on cryoPIV development since it is not pressurized, which makes the laser setup and seeding easier. Good flow tracer signals have been achieved for the complete temperature range from ambient to 100 K by injecting into the wind tunnel circuit oil droplets which were produced outside using DLR's Laskin generator.

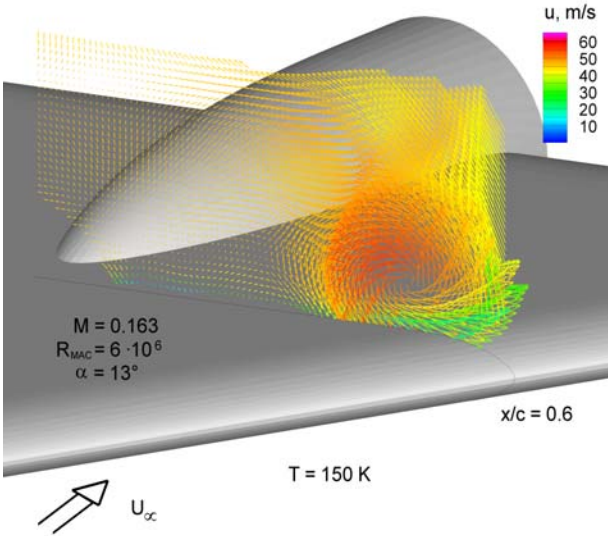

Figure 4. Result of a stereo PIV measurement of the flow field above a delta wing under cryogenic conditions in the DNW-KKK.

In ETW, the seeding substances may penetrate into the temperature shell and may damage the insulation material. Therefore, new substances and techniques are under development to generate flow tracers which produce suitable signals for PIV and can subsequently be easily removed from the wind tunnel circuit without leaving residues.

Although tiny water ice particles embedded in the flow were shown to be qualified as tracers at cryogenic flow temperatures, the underlying physics of their formation is complicated. Thus, tests are necessary to investigate the effects of ice particle formation, growth and sublimation as a function of the gas dew point, pressure and temperature. Such tests are currently being conducted within PETW and comprise different generation methods as well as alternative particle substances.

The high flow rates of the ETW reached at transonic speeds and the possible operation at a total pressure of 4.5 bar require also a specific design of the seeding generator which must be able to provide the required huge amounts of particles of high quality, with reproducible properties and the ability to work 'against' the high plenum pressure.

The large plenum of 10 m diameter and the limited optical access require that the optics forming a thin light sheet must be placed within the plenum in front of a test section window. All optical components, including the cameras, must be placed within temperature-controlled boxes. Since these components are no longer accessible after tunnel closure, all necessary adjustments have to be under remote control. The high energy pulse laser must be placed outside the wind tunnel and its light beam must be directed through windows to the test section. To compensate for structural changes and movement of the wind tunnel components when changing the gas pressure and/or temperature, the beam path must be adjustable using motorized mirrors during wind tunnel operation. The implementation of a cryoPIV system suited for ETW is ongoing work[5].

D. Image Pattern Correlation Technique (IPCT) and Backward Oriented Schlieren Technique (BOS)

Systematic aero-elastic and Reynolds number investigations on a full aircraft model in ETW have shown that even so called ‘rigid models’ are subject to deformation when tested in pressurized tunnels. Therefore it is necessary to assess the span-wise distribution of wing twist and bending during a wind tunnel run. Image Pattern Correlation Technique is a model deformation measurement technique which combines stereo photogrammetry and the cross correlation algorithms developed for PIV evaluation.

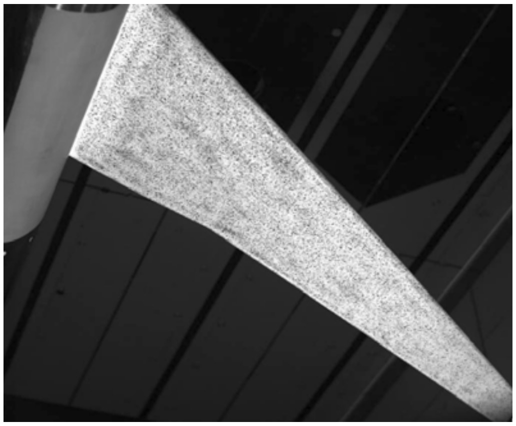

Figure 5. IPCT dot pattern on the wing of a cryogenic wind tunnel model tested in ETW.

A random dot pattern is applied on the surface of the measurement object, which enables a correlation to be determined between two stereo images taken at different times. With a 3D-calibration of the stereo setup and using the triangulation algorithms of photogrammetry, IPCT maps the 3D surface of the measured object and finally delivers the 3D-deformation of this surface.

The dot pattern to be superimposed onto the wing surface must fulfil certain requirements, based on the used camera, the camera lenses, the illumination light source and the geometrical configuration of the adopted setup. In ‘warm’ wind tunnels or flight tests, a computer-generated optimized dot pattern (specially adapted to this specific application) can be printed onto a bonding foil and subsequently affixed adhesively to the model or airplane wing. For the application under cryogenic conditions, the dot pattern has to be painted onto the model surface, since the application of adhesive foils in a cryogenic environment is not possible. To get the required good quality of the surface finish, the pattern is applied in 3 layers. First, the wing is primed with white paint, followed by the application of black speckles by means of a paintbrush. Afterwards a thin white layer is applied as a final coating. With a final grinding and polishing operation, the black dots become visible again, now being integrated into a smooth surface, and thereby not introducing surface roughness. Figure 5 shows a typical IPCT painting of a cryogenic wind tunnel model[6].

Apart from the particular manner of applying the dot patterns to be suited for cryogenic models, no further effort has to be made to implement an IPCT system into a cryogenic wind tunnel, since it can be operated using the same cameras and light sources as used with cryoTSP/PSP or cryoPIV, for example.

The Background Oriented Schlieren Method (BOS) is a very simple technique to visualize density gradients that is based on the deviation of light rays propagating through a refractive index gradient. Like IPCT, BOS also uses a random dot pattern, only in this case it has to be visible in the *background* of the camera image of the model part of interest (for instance the wind tunnel wall opposite to the side of the camera placement can be painted, Fig. 6).

The observed density gradient field is located between background and camera. The image of the background without density gradient in the field-of-view is used as a reference. The cross-correlation between reference and measurement image visualizes the gradient field, because the light beam refraction induced by the density (and hence refractive index) gradients is seen as a shift of the dot pattern on the background.

The adaptation of BOS for application under cryogenic wind tunnel conditions is similar to IPCT. Because the pattern is usually located on the wind tunnel wall, it is sufficient to apply the pattern in two layers (white background plus dots), without polishing the surface. A stereo BOS measurement was performed in ETW in 2004 to investigate the position of the wing-tip vortices as a function of Reynolds number[7].

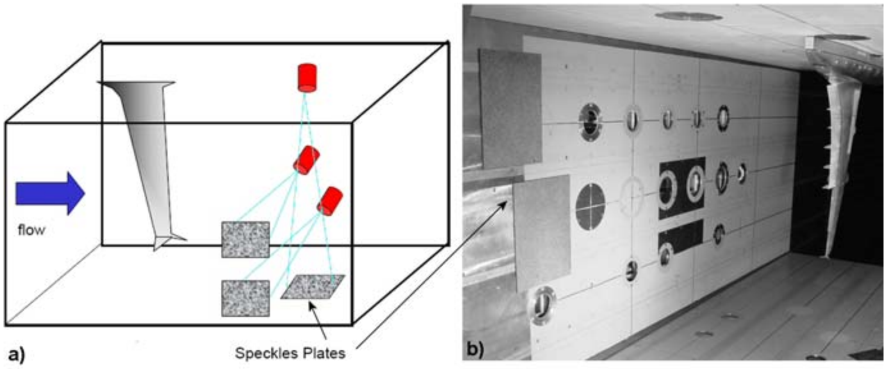

Figure 6. a) Sketch, and b) digital image of the BOS setup as used in the ETW cryogenic wind tunnel for a half model test.

For this test, plates were painted with a dot pattern and mounted onto the side wall opposite to that of the cameras, thus enabling the easier removal of the pattern after the test (see Fig.6).

E. Cryogenic Microphone Array Technique (CryoMAT)

Measurement techniques based on microphone-arrays are well-known and in common use on scaled models in 'warm' wind tunnels[8]. Usually, full-scale Reynolds numbers are not achieved and it is still an open question how aeroacoustic noise generation scales with the Reynolds number. To address this problem, the Reynolds number can be increased by performing acoustic measurements in cryogenic and pressurized wind tunnels.

Previous measurements have been successfully carried out by Stoker[9] in a mild cryogenic pressurized environment (≈ 230 K). At present, a special microphone array has been developed by the Institute of Aerodynamics and Flow Technology to investigate this measurement technique in a cryogenic environment down to 100 K.

The measurement principle of a microphone array is as follows: The position and the strength of sound sources radiated by an aircraft model in the wind tunnel can be measured by means of a large number of microphones which are usually placed in a two-dimensional plane. The source distribution on the model can be calculated and presented graphically in so called noise maps. These maps provide the possibility to identify dominant noise sources and are therefore an important tool to improve noise reduction on an airframe.

To develop a microphone array for a cryogenic environment, cold hardiness and long term stability of the array fairing and the electronic devices, especially the microphones, are the primary challenge. Thus, preliminary long-term tests with a test microphone array were performed under various conditions in the so-called climate chamber of the DNW-KKK in Cologne. For a first generic setup, a single rod representing a well-known aeroacoustic source was chosen. The source localization at temperatures down to 100 K was successfully accomplished in the DNW-KKK wind tunnel. The results showed good agreement with a prediction model for sound radiation of a cylinder in a flow[10,11].

Based on the described test array for cryogenic application, a microphone-array containing 144 electret microphones was developed. Acoustic array measurements were performed in a cryogenic wind tunnel at various Reynolds numbers in the range $1 \cdot 10^6$ to $9.0 \cdot 10^6$ (based on the aerodynamic chord length) using a 9.24% Dornier-728 half model. First results indicate different source mechanisms at the same Mach and Strouhal number but for different Reynolds number[11].

Figure 7 shows preliminary results where the source maps for two different Reynolds numbers are compared. At the increased Reynolds number (right image) the general noise level is increased and additionally, a source at the nacelle strake occurs which is not seen in the lower Reynolds number result.

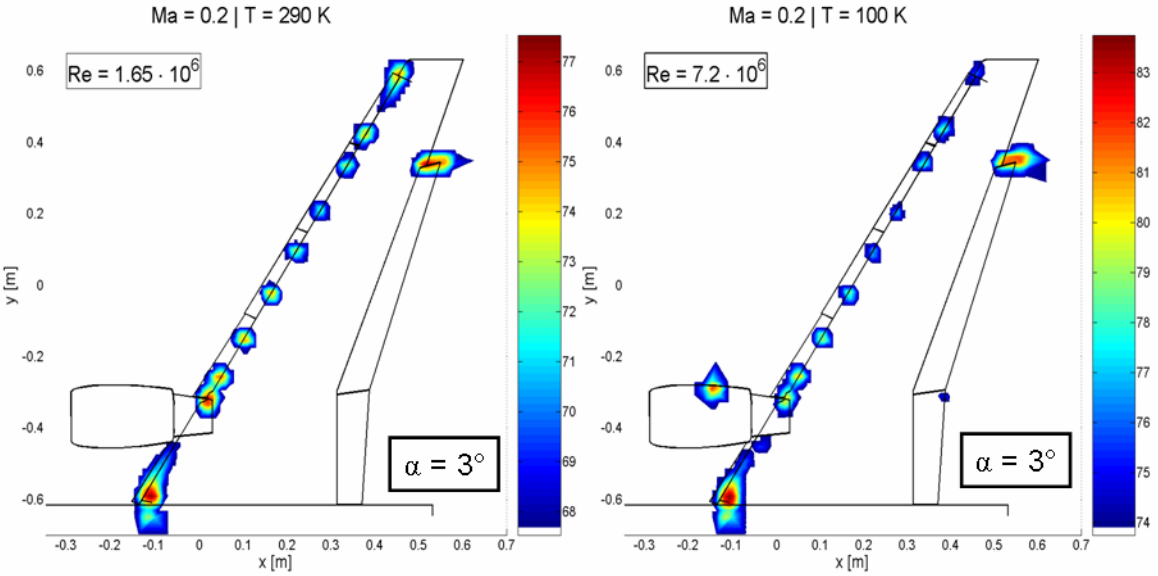

Figure 7. Source maps of the DO-728 scale model tested in the cryogenic wind tunnel DNW-KKK for M = 0.2 and AOA = 3°, but for different Reynolds numbers. a) T = 290 K, Re = 1.65 Mio, b) T = 100 K, Re = 7.2 Mio.

III. Final Remarks

It is obvious that the implementation of an experimental setup in a cryogenic wind tunnel is more difficult than in 'warm' wind tunnel testing. For example, the instruments have to be placed in heated housings with little space available, so that often standard cameras and light sources can not be used and miniaturized instruments must be found or newly developed. Especially in PETW, the possibility of installing optical equipment inside the plenum is limited. In cooperation with ETW, the DLR has nevertheless meanwhile successfully implemented a cryoTSP as well as a cryoPSP system using newly developed light sources operating at UV and blue wavelengths, and secondly, miniaturized but high dynamic range CCD cameras equipped with pinhole camera lenses.

The distance between the wind tunnel test section and the Main Tunnel Control Room (MTCR) of the ETW is rather large. Since the operator of the measurement system, as also the control and data acquisition PC's, must usually remain in the MTCR during the test, all signal cables connecting PC's and instruments (which are mounted behind the test section walls) have to bridge a distance of about 100 m, partly in cryogenic and partly in ambient environments. Since the instruments in their heated housings (thermo-boxes) are no longer accessible after the wind tunnel is closed, it is of major importance that all systems work reliably and that the adopted technique is sufficiently robust. Furthermore, instruments and sub-systems (such as aperture or focus adjustment on the camera lenses) must be remotely controlled.

A further problem in cryogenic wind tunnel testing is the presence of density gradients through which a light beam has to pass; these are caused by different temperatures of housing and wind tunnel gas (convective distortions) and by pressure effects in a pressurized wind tunnel. Such 'aero-optical' effects have to be addressed during the design of the experiment and the final evaluation as well.

If instruments have to be used which are sensitive to high pressure or pressure changes in general (some cameras, lamps or laser), they have to be mounted in heated and *pressure-tight* housings, making the setup more complicated. Or alternatively, the instruments have to be mounted outside the wind tunnel plenum, such as is the case with high energy lasers where the laser beam has to be brought into the test section using pressure-sealed silica glass windows and cryo-qualified mirrors.

Most of the technical problems related to cryogenic use of an image-based measurement system had been solved prior to the first cryoTSP test in the ETW wind tunnel in 2003[1]. Concerning camera implementation, operation of lamps or LED's, signal transfer and reliability of equipment as well as miniaturization, techniques such as IPCT, BOS, cryoPSP which had been implemented after these first tests could benefit from the gained experience..

CryoTSP, IPCT and BOS are hence now available for different cryogenic wind tunnels. CryoPSP, however, is still under development, mainly since the paint itself still has to be further improved. CryoPIV still has to cope with the challenge of developing a seeding suitable for the ETW wind tunnel, and to operate the high energy lasers in the cryogenic environment.

The cryogenic Microphone Array Technique (cryoMAT) has successfully been demonstrated in the non-pressurized (low speed) DNW-KKK wind tunnel and further development is in progress. A Reynolds number dependency of aeroacoustic sources is observable. In order to predict full-scale airframe noise based on small-scale model measurements via the phased microphone array measurement technique, future work should also be focussed on acquiring aeroacoustic data in an environment which is both pressurized and cryogenic.

In summary, extrapolating from the remarkable progress made with the use of advanced optical and acoustical measurement techniques in cryogenic environment, it can be expected that in a few years such measurement techniques will be available for industrial testing at high Reynolds numbers in large cryogenic wind tunnels as well.

References

[1] Fey, U., Engler, R.H., Egami, Y., Iijima, Y., Asai, K. Jansen, U. and Quest, J.: "Transition Detection by Temperature Sensitive Paint at Cryogenic Temperatures in the European Transonic Windtunnel (ETW)*", 20th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF)*, Göttingen, Germany, August 25.–29., 2003, pp. 77-88.

[2] Egami, Y., Fey, U. and Quest, J: "Development of New Two-Component TSP for Cryogenic Testing", *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, Jan. 8-11, 2007, *AIAA*-2007-1062

[3] Egami, Y., Fey, U. and Engler, R.H.: "Appropriate Selection of Pressure-Sensitive Paint for Cryogenic Wind Tunnels", *44th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, Jan. 9-12, 2006, *AIAA*-2006-1045

[4] Schröder, A., Agocs, J., Frahnert, H., Otter, D., Mattner, H., Kompenhans, J. and Konrath, R.: "Application of Stereo PIV to the VFE-2 65 Delta Wing Configuration at Sub- and Transonic Speeds", *AIAA Paper 2006*–3486, 2006

[5] Konrath, R., Otter, D., Fey, U. and Quest, J.: “Adaptation of PIV for Application in Cryogenic Pressurized Wind Tunnel Facilities at High Reynolds Numbers”, submitted to: *15th International Lisbon Symposium on the Application of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, July. 5-8, 2010

[6] Hurst, D., Frahnert, H., Schinkel, R.van, Quix, H. and Le Sant, Y.: “Benchmark Testing of the Model Deformation Measurement Systems Developed Within the European Windtunnel Association (EWA)”, Conference Proceedings, CD-ROM (ceas2007-336), *1st CEAS European Air and Space Conference*, Berlin, 2007, p. 1–10

[7] Pallek, D. and Klinge, F.: “Studies of Reynolds Number Effects on Wing Tip Vortex Positions by Means of Laser Light Sheet (LLS) and Background Oriented Schlieren (BOS) Technique Under Cryogenic Conditions.”, in: C. Tropea, S. Jakirlic, H-J. Heinemann, R. Henke and H. Hönlinger [Ed.]: *Notes on Numerical Fluid Mechanics and Multidisciplinary Design 96*, 2008, Springer, p.104 – 112

[8] Koop, L., Sijtsma, P., and Oerlemans, S., “Noise Source Localization in Closed Test Sections with Microphone Arrays,” *1st CEAS European Air and Space Conference*, 2007, pp. 1 – 10.

[9] Stoker, R.W., Gutierrez, R., Larssen, J.v., Underbrink, J.R., Gatlin, G.M. and Spells, C.: “High Reynolds Number Aeroacoustic Testing in NASA´s National Transionic Facility (NTF),” *46th AIAA Aerospace Science Meeting and Exhibit*, 2008.

[10] Ahlefeldt, T. and Koop, L.: “Microphone Array Measurement in a Cryogenic Wind Tunnel”, *15th AIAA/CEAS Aeroacoustic Conference*, Miami, Fl, USA, May 11-13, 2009.

[11] Ahlefeldt, T. and Koop, L.: “Aeroacoustic High Reynolds Number Measurements in a Cryogenic Wind Tunnel”, *13th CEAS-ASC 2009 Workshop & 4th Scientific Workshop X3-NOISE*, Bucharest, Romania, Oct. 1-2, 2009