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Quantitative Wind Tunnel Studies Using Pressure- and Temperature Sensitive Paints

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Abstract : The pressure sensitive paint (PSP) intensity and lifetime system is an optical measurement technique to investigate absolute pressure fields on model surfaces for basic research in laboratories, industrial wind tunnels or high speed rotating turbo machines. Detailed qualitative and quantitative information and understanding of flow phenomena can be obtained in speed ranges from U_∞ =20 m/s up to Ma= 5.0. A number of projects of industrial interest has been investigated in different wind tunnels covering low speed, transonic, trisonic and cryogenic facilities. The influence of the main error sources for the components of the PSP system have been checked. Comparison of experimental pressure fields obtained by means of PSP and the results of numerical calculations have been carried out. Different wind tunnel models ranging from basic configurations such as a cropped delta wing to a complex half model of a large propeller-driven transport aircraft with all flaps, rudders and shrouds, and rotating or oscillating models as well as Reynolds number effects on models have been investigated.

Keywords : Pressure sensitive paint, PSP, Temperature sensitive paint, TSP, Optical sensors.

1. Introduction

The determination of instantaneous two dimensional pressure distributions on the surface of a model in test facilities like wind tunnels or turbo machines by the application of a pressure sensitive paint can be construed as a major advancement in the field of non-intrusive measurement techniques in aerodynamics. The "Pressure Sensitive Paint (PSP)" method allows not only to obtain qualitative pressure images, but also to obtain quantitative absolute pressure values all over the surface of the model, without introducing flow-disturbing probes or affecting the surface of the model. The PSP measurement technique is based on the oxygen-quenching process related to the deactivation of photo-chemically excited molecules with oxygen. Different intensities are recognizable on the PSP-coated surface of the model, which correspond to the local oxygen concentration and thus to the local pressure. Such a fluorescence image arising under the flow conditions in a wind tunnel can be recorded using CCD-cameras or photomultipliers, with an appropriate filter for the emission of the luminescent light. The final pressure map is obtained using sophisticated image processing algorithms. A drawback of the PSP technique is that impurities of the model's surface, such as oil, water, ice, solvents or large dust particles in the test facility may adversely affect the achievable accuracy or may even completely damage the optical pressure sensor. Basic research studies and industrial tests using the PSP-technique have been carried out in the laboratories of DLR Göttingen as well as in different industrial wind tunnels in Göttingen and Europe including test facilities for turbomachinery of the EPFL Lausanne and the University of Darmstadt. Typical applications of PSP include the qualitative detection and measurement of quantitative pressure data of "footprints" of the vortex field near the model surface, the detection of vortex development and its interactions, shock locations, leakage effects on turbine blades as a function of the angle attack, Mach number or Reynolds number. The sensitivity of the used optical pressure sensor belonging to the two component DLR02 paint is optimized for the transonic pressure range. This paint also can be used for low speed and hypersonic applications. To increase the accuracy a new calibration procedure has been developed which allows computing the individual calibration constants for each pixel of the image recorded by a scientific 16-bit CCD camera. Under static conditions, a resolution of about ± 1 mbar with a response time of the order of 0.3 s could be achieved. For unsteady investigations, several "fast" paints have also been developed for applications such as for rotating models and turbomachinery with response times of about 1 ms.

2. Optical Pressure Sensor (Physical Principles)

The PSP measurement method is based on the deactivation of photochemically excited molecules (i.e. luminophores) by oxygen molecules. When luminophores absorb light within a certain wavelength range, they are excited from the energy state to a higher energy state. These molecules can leave the high energy level either through emission of light (luminescence) or even without radiation. The interaction of excited luminophores with oxygen molecules increases the possibility of radiation-free processes. Possible energy levels (electron level, vibration level and rotation level) of molecules are quantized with respect to energy. Under normal conditions, almost all molecules possess "strongly prohibited" transitions. The probability of a transition between different energy levels of a molecule is determined by the electronic structure of the initial and the final state.

The absorption of light and thus the excitation of a molecule M having the basic energy status S_o and presently being at a higher energy level S_1 can be described as:

$$I_a = M_{S0} + h\nu \rightarrow M_{S1} \quad (1)$$
$$k_{fl} = M_{S1} \rightarrow M_{S0} + h\nu_f \quad (2)$$
$$k_{nr} = M_{S1} \rightarrow M_{S0} + \text{heat} \quad (3)$$
$$k_q = M_{S1} + O_2 = M_{S0} + O^*_2 \quad (4)$$

with I_a-Photon absorption, k_{fl}- Luminescence, k_{nr}- Nonradiative decay, k_q- Quenching and O^*_2 as the meta stable oxygen. These schemes lead to the Stern-Volmer (SV) expressions, quantitatively relating lifetime and luminescence intensity to the quencher concentration, which becomes the basis for the PSP intensity method for non time resolved measurements as:

$$\frac{I_{(p=0)}}{I} = 1 + k_{SV} \cdot S \cdot 0.21 \cdot p \quad (5)$$

where $I_{(p=0)}$ - intensity for vacuum conditions, k_{SV} - Stern-Volmer constant and S - solubility coefficient.

3. Designs of Different Pressure Sensors

In principle, the optical pressure sensor must be quenchable with oxygen present in test facilities like wind tunnels and at the same time enable the measurement of the partial pressure of oxygen. Therefore, it is clear that such a sensor must consist of two parts, namely, a binder which is permeable for the diffusion of oxygen (e.g. a polymer) and a luminophore for quenching. There exist open systems like anodized aluminium with open wholes of ≈ 50 nm diameter and in non open systems, like polymers with a defined diffusion constant the diffusion of oxygen into the binder is a time-dependent process, in which the thickness l of the polymer layer of the sensor has a significant influence. This can be described for polymer binders as follows:

$$t_{relaxation} = \frac{4l^2}{\pi^2 D} \tag{6}$$

where D is the oxygen diffusion coefficient of the binder. The permeability of the binder should not be too high to ensure that not all of the excited luminophores are quenched by oxygen. Besides, it must be ensured that the luminophores can be quenched by the oxygen diffused through the binder within their lifetime τ, otherwise no pressure-dependent intensity variation can be observed. Thus, optimal characteristics of the optical sensor for the different cases of application with reference to the maximum pressure changes to be expected (transonic range 0.3 to 1.5 bar, low speed range 0.8 to 1.2 bar) for the selection of the binder for the number of luminophores in the binder are obtained. In addition, the optical pressure sensor must withstand the normal and tangential aerodynamic forces. Furthermore it must be as thin, flat and smooth as possible and have uniform characteristics over the entire surface of the model. For obtaining a smooth optical sensor on the entire surface, a spray gun is usually employed. The paint sensor typically consists of two polymeric layers, which are applied consecutively to the models surface. These two layers are a white screen layer as a base and a transparent active layer with two different luminophores (one for pressure detection and one for intensity correction) on top.

3.1 Characteristics and Calibration of the Optical Pressure Sensors

In medicine as well as in biology, a large number of molecules are known which can be used as oxygen sensors. For the use as a luminophore, i.e., molecules with sufficiently long lifetime for quenching with oxygen, platinum (PtOEP)- and ruthenium-complexes such as tris-2,2'bipyridyl-ruthenium(II) can be employed. For excitation of these luminophores, the blue line (λ = 488 nm) of an argon-ion laser can be used. In addition, Pyrene (belonging to a group of aromatic hydrocarbons) is well known as a luminophore in optical sensors. Here, UV light of the wavelength (λ = 337±10 nm) from a Xenon lamp can be used for the excitation of luminophores. From the calibration curves of these paints it is known that pyrene has a more linear behavior in comparison to ruthenium. The pressure sensitivity of ruthenium based paints appears to be larger than that of pyrene based paints. The error due to the temperature effects is smaller for pyrene (0.2%/°C) as compared to 5%/°C for ruthenium. The lifetime of ruthenium is of the order of 1-2 microseconds whereas the lifetime for pyrene it is about 50-100 ns and therefore, it is a more suitable paint for investigation of fast processes.

4. Components of the Intensity PSP System

The PSP system is mainly composed of several subsystems and hardware as described below. The schematic of the test set-up in Fig. 1 shows all the essential optical and electrical components of the DLR 360° PSP system. This system consists of various illumination devices, twin CCD cameras for pressure and reference images (because of binary paint pressure sensitive molecules and reference molecules without pressure and temperature dependency), a local image and data acquisition system and an external calibration chamber. In order to achieve a high flexibility for the most different wind tunnel tests modular and highly sophisticated acquisition and processing subsystems are required. The mobile DLR system includes camera boards, synchronization units for eight cameras, light source trigger, a fast graphic processor board and several 500 Gbyte hard disks for data storage. A user friendly software package ToPas (Three dimensional optical Pressure analyzing system), running under UNIX and Linux has been developed in order to facilitate the management of all the tasks executed by this powerful PSP hardware system.

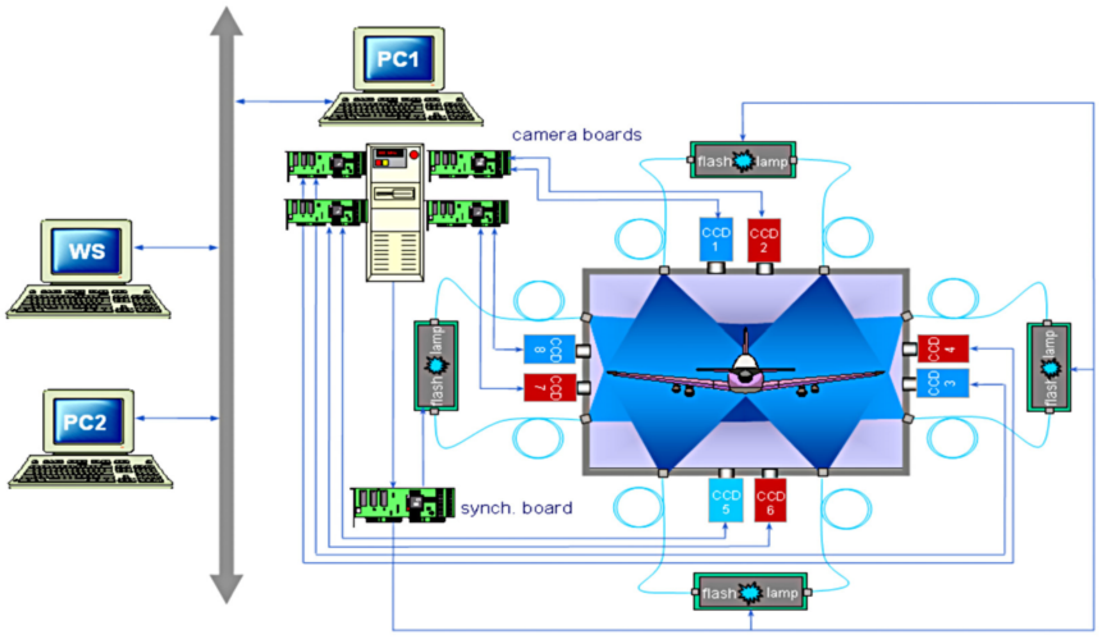

Fig. 1. Sketch and data flow of the 360° PSP intensity system, based on 4 twin cameras.

This configuration allows extracting absolute values of pressure by means of simultaneous processing of the acquired and the calibration data. Using a 3d-grid for the investigated model, a high quality map of the pressure data with accurate pressure or Cp values on each grid node can be presented to the wind tunnel clients 2 min after acquisition of the 2d-images from all eight CCD cameras.

5. Results

5.1 Low Speed Tests

A real challenge for the application of the PSP technique in a wind tunnel are measurements under low speed conditions including strong temperature effects as visible in Fig. 2. Here a half-model of a propeller-driven, large transport aircraft was investigated using DLR02 paint in the 2 m x 2 m test section of the LSWT wind tunnel of Airbus Bremen, Germany. The tunnel speed was varied from

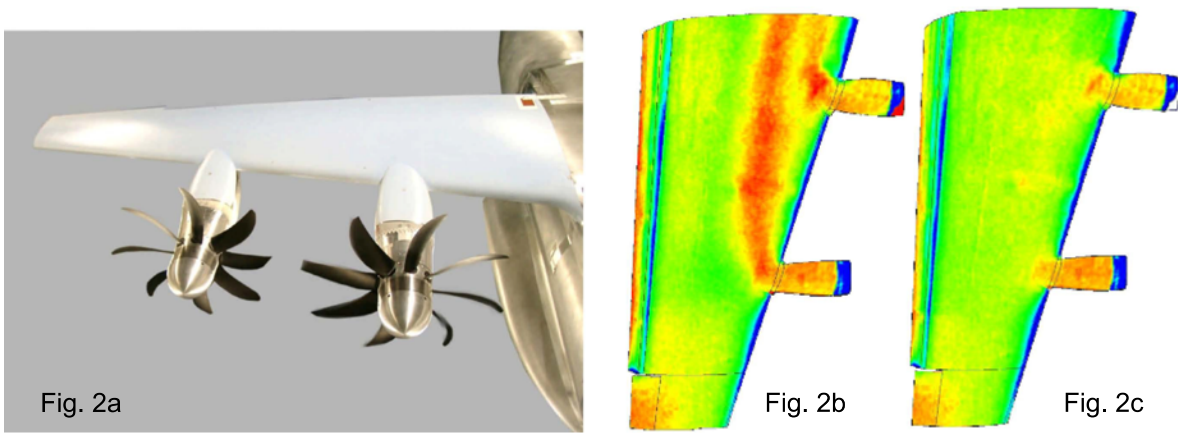

Fig. 2. PSP pressure distribution on the half-model of propeller-driven large transport aircraft model for U_∞= 60 m/s and α = 16° with IR temperature correction on the areas as visible in the PSP results.

U_∞ = 30 to 60 m/s and different angles of attack from α = -5° to +18° have been selected. The most difficult part was the temperature correction of the PSP raw data, since strong temperature gradients on the model surface have been created by the air pressure tubes which were driving the counter rotating propellers. The air used to operate the propellers was of a temperature of +40 °C and the expanded air comming out of the propellers decreased down to –20 °C in temperature. In order to obtain a high accuracy the quantitative PSP data was taken by using two scientific grade 16-bit CCD cameras with high pixel resolution simultaneously for the "pressure image" and the "intensity image". In parallel the temperature of the binary-paint coated model was measured with an IR-camera. Figure 2a shows the coated half model in the wind tunnel and Fig. 2b the non temperature corrected PSP image under flow condition. Figure 2c shows the final result after pixel by pixel temperature correction between the PSP image and IR image.

5.2 Load Calculation in Transonic Flow (360° PSP Measurements)

For comparison of forces and moments obtained with the PSP technique to balance data, the EADS MAKO model was installed in the DNW-HST wind tunnel in Amsterdam. The basic MAKO model and additional 40 exchangeable model parts like flaps and rudders were fully coated with DLR02 paint. The arrangement, shown in Fig. 1, was used to obtain a 360° view of the complete aircraft (see Fig. 3). These pressure maps were used for later integration to calculate the total loads of the MAKO model and of single components like the horizontal tail (as shown in Fig. 4). The latter was chosen because a hinge moment balance was installed in the left part of the tail wing.

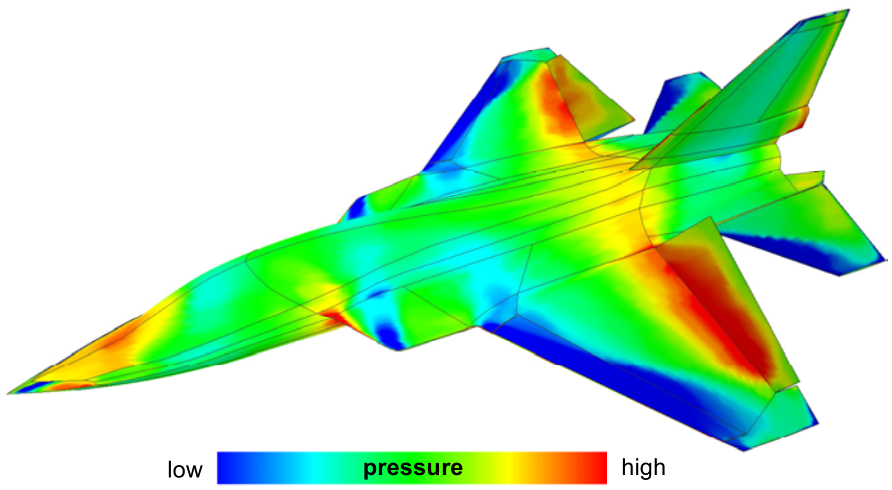

Fig. 3. Completely PSP coated MAKO model with absolute pressure distribution to calculate loads.

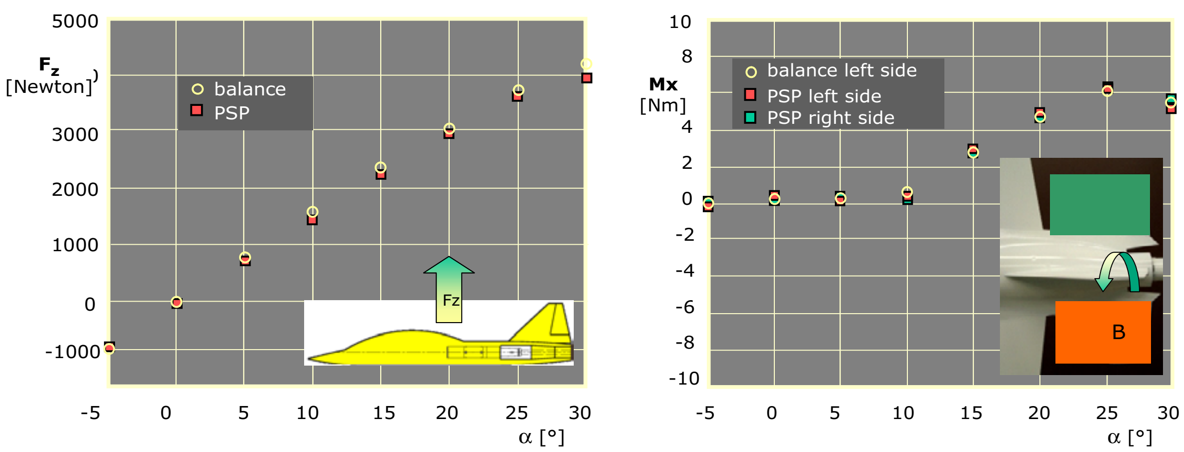

Fig. 4. Comparison of normal forces Fz and bending moments Mx of the MAKO model in the DNW-HST.

The main goal of this test was to obtain detailed information about the accuracy of the PSP data. The Mach numbers were chosen in-between Ma= 0.4 and 1.0, at angles of attack α = -5° to 30°. In addition, side slip angles β = -10° to +10° were used. The achieved results have shown that the PSP method can be an excellent tool to detect the sources of separation on the model's surface, because balances give information averaged over the complete model, or model parts equipped with balances, only. Asymmetric pressure distributions on the wings as obtained by means of PSP made these effects obvious. As far as the quantitative data are concerned the difference between hinge moment balance and PSP was about ~ 5% in moments for symmetric flow and using lenses with a large zoom factor (see Fig. 4). On-line available PSP data provide a fast overview over the pressure field over the very wide flight envelope of the aircraft, both in speed and angle of attack. This helps considerably to reduce the efforts, costs and time required for numerical calculations of the pressure field and the loads.

5.3 Rotating Delta Wing Model Compared with CFD Calculations

Figure 5 shows a representative comparison between Euler/Navier-Stokes code calculations and PSP measurements for a delta wing model rolling at f = 10 Hz in the DNW TWG transonic wind tunnel in

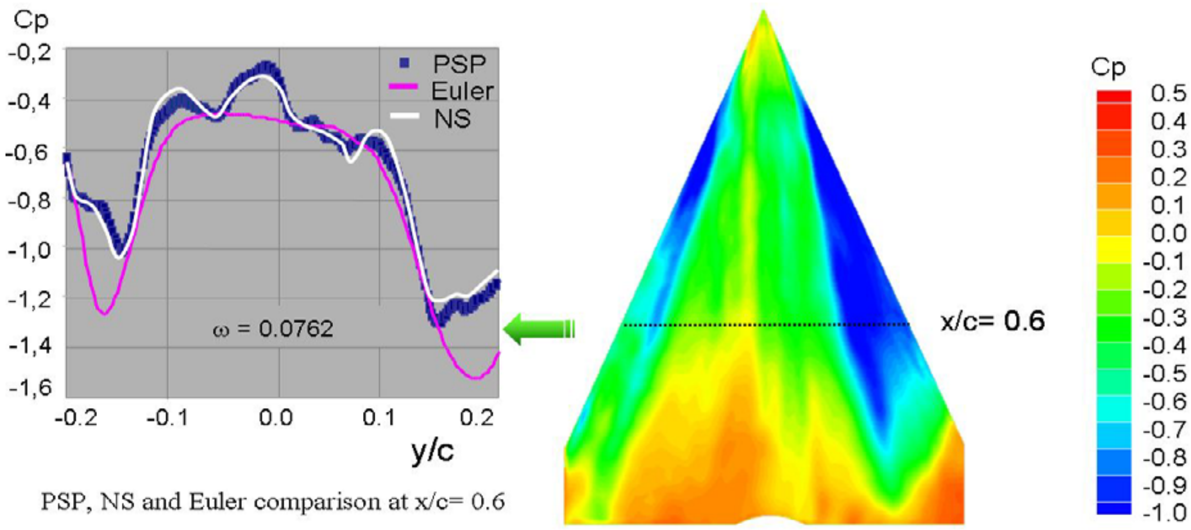

Fig. 5. PSP pressure distribution on a delta wing at Ma = 0.8, α = 17°, Φ = 30°, f = 10 Hz, (ω = 0.0762).

Göttingen. The agreement between measurements and calculations is obvious. Moreover, PSP measurements are an excellent tool to correct the initial and boundary conditions for numerical calculations because the flow along the leading edge and at the cropped area is not well calculated - especially in areas with fine vortex structures as visible for the Navier-Stokes solutions. To obtain these experimental results it was necessary to use a single, powerful flash lamp with pulse duration of 1 ms in order to have enough energy to expose a single PSP image within this time period. A simple calculation for a frequency of 10 Hz gives a 3.6 degree rotation during the integration time of 1 ms of the PSP system.

5.4 TSP Measurements in a Cryogenic Windtunnel

The identification of laminar-turbulent boundary layer transition on wind tunnel models provides essential data for modern wing design. However, simulating true flight Reynolds numbers with scaled models requires the usage of cryogenic wind tunnels such as the European Transonic Windtunnel (ETW) in Cologne. The detection of the laminar-turbulent transition can be done via the detection of temperature changes on the wing, e.g. with IR techniques.

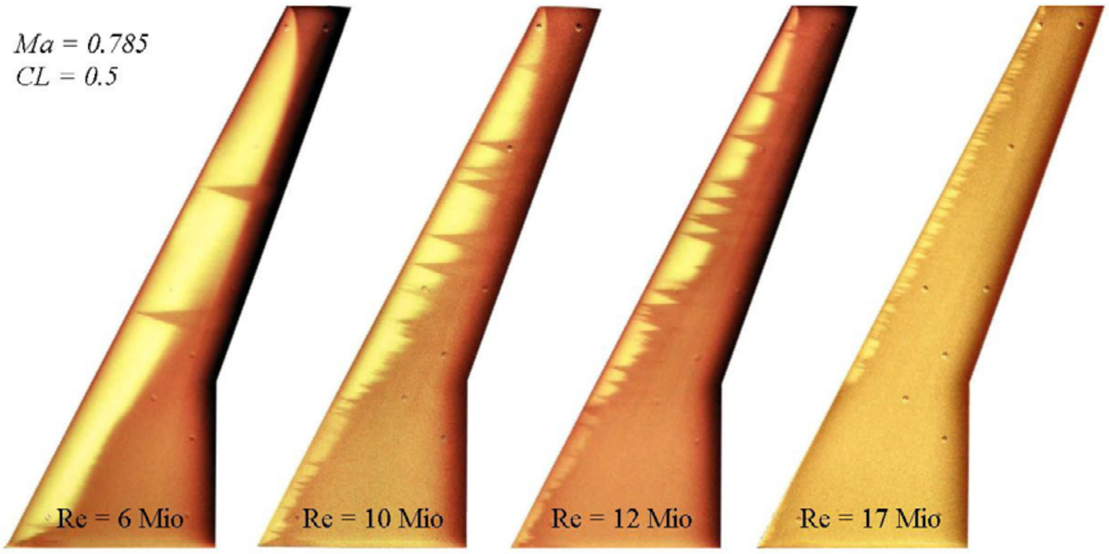

Fig. 6. Development of transition as a function of Reynolds number.

However, in cryogenic testing, IR imaging becomes quite difficult because of the reduction in radiated energy and the shift to longer wavelengths. Therefore, the temperature sensitive paint (TSP) technique has become a promising alternative here. As an example, Fig. 6 shows TSP result images taken in a co-operativ work between the three partners DLR, JAXA and ETW at different Reynolds numbers and at cryogenic temperatures (in the range T = 120 – 180 K).

6. Conclusion

It has been shown that the PSP and TSP measurement techniques can be used in a wide range of applications in aerodynamic wind tunnels. A number of tests in the low speed as well as in transonic and cryogenic flow regimes have been performed in European wind tunnels, the results of which demonstrate the high level of accuracy, which can be achieved. It was shown that the PSP technique not only offers quantitative pressures maps on the surface of the wind tunnel model, but also gives useful initial and boundary conditions necessary for numerical flow simulations. A good agreement has been observed between the conventional pressure measurement technique and the intensity PSP technique in the all the different wind tunnel tests.

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Author Profile

Rolf H. Engler: He received his Dipl. Ing. degree at the Ing.-Academy of Wolfenbüttel in the field of air conditioning in 1969. After three years in industry, he started a study at the University of Göttingen and received his Dipl. Physiker degree in 1979 for Vortex investigation using Ultrasonic pulses. In 1986 he received the Dr. rer. nat. degree for experimental investigations of vortex breakdown using a newly developed non intrusive technique – t he Ultrasonic-Laser-Method. Since 1991 he works on pressure-sensitive-paint techniques (PSP) in different wind tunnels of DLR and Europe and is leader of the PSP team at DLR.

Uwe Fey: He studied physics at the University of Göttingen and received his Diploma in 1994 for an experimental investigation of the laminar-turbulent transition of the cylinder wake. He continued his work at the Max-Planck Institut for Fluid Dynamics in Göttingen and in 1997 he received his Ph.D. Thereafter he joined the Research Center Rossendorf (FZR) near Dresden and worked in the field of magneto-hydrodynamics and was involved in experiments on boundary layer control by means of electromagnetic forces. Since 2002 he is a member of the PSP team at DLR Göttingen and responsible for cryogenic PSP and TSP in co-operation with ETW.

Ulrich Henne: He studied physics at the University Hannover. In his diploma work he investigated inelastic collisions between He^+ ions and Ne atoms at low energies which he finished in 1989. For his Ph.D. thesis he joined the Max-Planck Institute for Fluid Mechanics in Göttingen where he worked on ionization and electron capture of large He clusters. After receiving his doctoral degree in 1996 from the University Göttingen he worked at the PTB in Braunschweig on determination of cross sections of low energy electron ionization. Since 2001 he works as a researcher in the field of PSP development at DLR in Göttingen.

Christian Klein: He studied physics at the University of Göttingen and joined for his diploma work the Max-Planck Institute for Fluid Mechanics in Göttingen. The diploma work was an experimental investigation of turbulent channel flow using LDV. He received his diploma degree in 1994. For his following Ph.D. thesis, he investigated the application of Pressure Sensitive Paint (PSP) for transonic flows at the German Aerospace Center in Göttingen. He received his doctoral degree in 1997 from the University of Göttingen. Currently, he works as a researcher in the field of PSP applications for low-speed and unsteady flows.

Werner E. Sachs: His first study of mechanical engineering with priority of aerodynamics at the University of Paderborn he finished in 1975. The second study of Mathematics at the Georg-August-University of Göttingen was finished at 1983. Since 1983 he is scientist at DLR working in different sections: basic research in commission for (ESA) in the field of structure dynamics of satellites. Wind tunnel flutter investigations of turbine and compressor cascades, hereafter he finished with the degree of Dr.-Ing. at the RWTH Aachen. From 1990 to 2000 he was head of the electronic data processing and measurement technique group at the main division of wind tunnels at DLR Göttingen. Since 2000 he mainly develops software (ToPas) in the DLR PSP team.