13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

Pressure Sensitive Paint Application in Low-Speed Flows

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ABSTRACT

Pressure field measurements on a wing profile are conducted to evaluate the accuracy of measurement system using Binary Pressure Sensitive Paint (PSP) for low speed (40-60 m/sec) environments. A part of the wing surface was coated with binary paint B1 from Optrod Ltd. Two different light sources, a Xenon - flash lamp and a nitrogen-laser were used for paint excitation and the resulting fluorescence fields in two spectral band length were acquired by 16 bit CCD slow scan camera with appropriate filters. Results shows that the optical pressure measurement system with binary paint can achieve pressure resolution better than 1 mbar.

NOMENCLATURE

I	= luminescence intensity
K_q	= quenching constant
PO_2	= partial pressure of oxygen
p	= local static pressure
A,B,C	= calibration coefficients of a paint
t	= response time
l	= thickness of the binder layer
D	= diffusion coefficient of oxygen
Λ	= aspect ratio

SUBSCRIPTS

0	= absence of oxygen (vacuum conditions)
ref	= reference condition

INTRODUCTION

The physical basis of all Pressure Sensitive Paint (PSP) formulations is the oxygen-quenching process in which excited luminophore molecules are deactivated by oxygen. Luminophore molecules are placed in a binder layer on the model surface and are excited by an appropriate light source. Oxygen from airflow can diffuse into binder layer and oxygen concentration in the layer is the function of local static pressure on the upper surface of the binder. Resulting luminescent intensity distribution reveals the static pressure distribution on the model [1]. The PSP method gives quantitative as well as qualitative pressure distribution images of the complete observed model surfaces [2] without significant disturbances. This method could be used also for flow visualization and to provide detailed aerodynamic quantitative static pressure information about the models aerodynamic. The PSP techniques have been widely used in wind tunnels for investigations in transonic - and supersonic flow [3]. For these fields of interest, the absolute pressure changes on the model surface are rather large. Therefore also changes in the detectable luminescence levels are larger. Low-speed flows (Ma<0.3) produce in comparison to the transonic - and supersonic flows relatively small pressure changes on the models surface and therefore the variation of luminescence levels due to pressure change is quite small. However, some groups already measured pressure in low-speed flows using the different existing PSP techniques:

Group	Model	Ma	Δp_{max}[psi]
Morris et al. [4]	Delta wing	0.17	0.3
McLachlan et al. [5]	NACA0012	0.30	1
INTECO [6]	Car-model	0.12	0.12
Sullivan [7]	Jet interaction		3

Table 1: Previously PSP measurements in low-speed flow.

In the described experiment a measurement system and data processing algorithms were optimized to achieve a good the signal-to-noise ratio (SNR) and to reduce influence of possible measurement errors. With this system, reliable experimental results were obtained for flow velocities down to U_∞ = 40m/s. A sample of data is presented to show some aerodynamic effects on the investigated wing profile and to demonstrate the comparison between PSP results and conventional pressure taps data.

PSP BASIS

PSP techniques are based on the deactivation of photochemical-excited organic molecules, so called luminophores, by oxygen molecules. This oxygen-quenching process of luminescence was first discovered and described by Kautsky and Hirsch [8] in 1935 and will be briefly reviewed in this paragraph.

The behavior of photoluminescence of a luminophore quenched by oxygen molecules can be described by the Stern-Volmer relation [1]:

$$I_0/I = 1 + K_q PO_2 , \qquad (1)$$

where I_0 is the photoluminescence in the absence of oxygen (vacuum), I the detected photoluminescence, K_q the quenching constant, and PO_2 is the partial pressure of oxygen. K_q is a function of temperature.

In the widely used pressure sensitive paint formulations, the luminophores (e.g. ruthenium, pyrene) are located in a polymeric binder material (e.g. silicon rubber). The binder compound is permeable to the oxygen molecules. To calculate the static pressure values from a measured intensity distribution for such paint formulations the second order approximation is more useful:

$$p = A(T) + B(T)(I_{ref}/I) + C(T)(I_{ref}/I)^2, \qquad (2)$$

where p is the local static pressure, A,B,C are temperature dependent calibration coefficients of the pressure sensitive paint formulation, which can be determined in laboratory or pressurized wind-tunnel and I_{ref} is the corresponding intensity value for a constant reference pressure. Thus, using a ratio of images taken at two pressure conditions ("wind on" and "wind off") allows determining of static pressures over the surface of interest. A problem that occurs when using PSP in this intensity method is the model displacements, uncertainties of the temperature field on the model surface, excitation light non-stability, the spread of exposure time, and the luminescence light scattering on the adjacent model parts or test section walls (self illumination). Aerodynamic forces acting on the model change their position relative to the light source and image acquisition system. Alignment of "wind off" and "wind on" images doesn't totally eliminate influence of model displacement and deformation [2] and [9]. Influence of the temperature field uncertainties can be minimized by direct measurements of the temperature distributions on the model surface, by using PSP formulations with small temperature sensitivity or (and) by estimation of the temperature field on the base of measured pressure fields and some assumption about heat flux on the model surface [10]. A more detailed description of different pressure sensitive paint formulations as well as a more complex theoretical background is presented in [10] and [11].

EXPERIMENTAL SETUP

The presented measurements were performed in the Low-Speed-Wind-Tunnel (LSWT) of Daimler-Benz Aerospace in Bremen. This Eiffel type wind tunnel with 1.8m x 2.0m test section is a continuously driven facility operating at speeds between U_∞= 20 and 65m/sec. For PSP tests a wall plate element, Fig. 1, was built for the fast implementation of the excitation illuminators and CCD camera observation

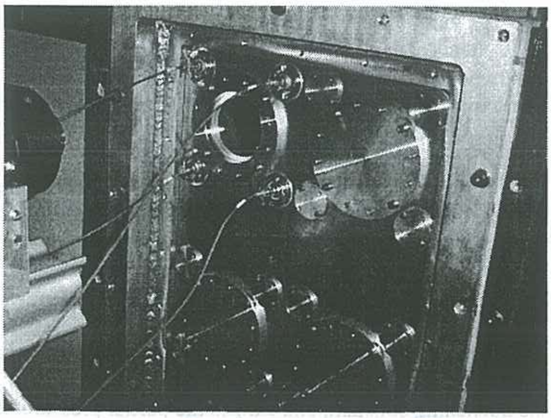

Fig. 1 Observation window, illuminators and Camera.

The investigated surface is a part of the suction side of a wing with a constant profile. Fig.2 shows a photo of the PSP coated part of the investigated wing model. Along the pressure taps no PSP coating was applied.

The B1 binary paint formulation from Optrod Ltd., based on pyren as luminophore, was used for the measurements. This paint consists of a screen layer, adhesive layer and an active layer with a total thickness about 50 µm and a response time 0.5s.

Typical calibration curves for different PSP formulations are presented in Fig.3.

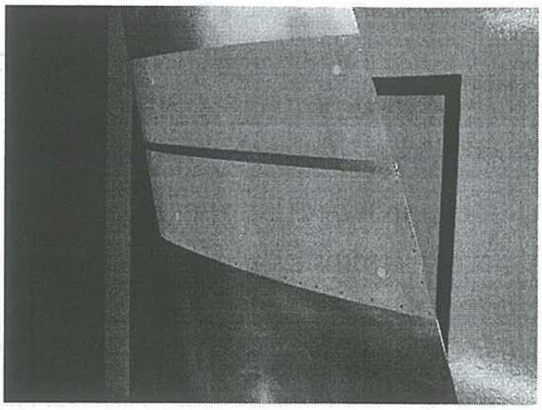

Fig. 2 Investigated model in the test section with PSP coated area

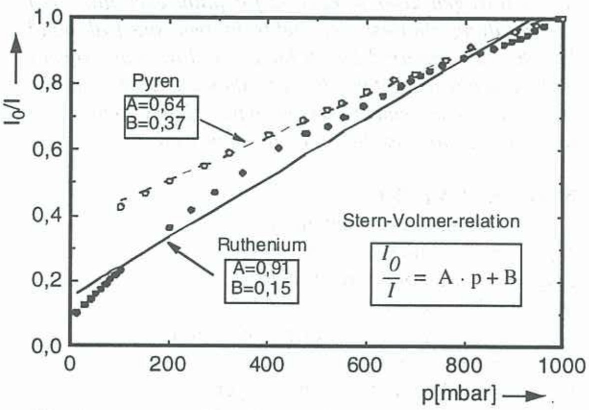

Fig. 3 Calibration curves for different paint

The emission of the PSP depends on the excitation intensity. That means the instabilities of excitation light and model movement or model deformations relative to the light source will leads directly to an error in the pressure measurements. To minimize this error a binary paint composition is necessary. Binary composition provides the possibility to acquire simultaneously additional reference image, which contains information about local excitation intensity. The excitation intensity fluctuations for Xenon flash lamp or the nitrogen-laser integrated for expose time 1 sec can be estimated as 1% that provides significant input in the measurement error without using binary paint. Fig.4 shows emission spectra of binary paint for different absolute pressures.

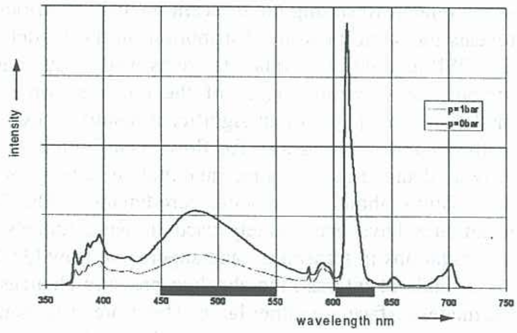

Fig. 4 Emission spectra of binary paint for different absolute pressures and constant temperature.

The emission band from 425nm to 550nm is used to acquire pressure sensitive image and the emission band from 610nm to 630nm is used to obtain the "excitation reference" image. Using the above mentioned Xenon flash-lamp light source for excitation and a scientific grade 16bit, 1024x1024 pixel CCD slow-scan camera, exposure times of approximately 10s can be realized for each "pressure/reference" image. These images were acquired sequentially by one camera using a filter shifting system. Such approach doesn't eliminate totally time non-stability of the light source but is affordable taking into consideration long exposure time. Fig.5 shows the basic PSP system composition for this wind tunnel test.

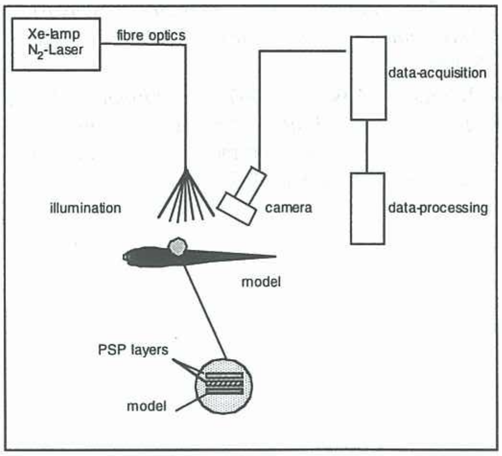

Fig. 5 : Schematic diagram of experimental set-up.

Since pressure sensitives paints are also sensitive to temperature, the temperature of the stream was controlled during the run to minimize the temperature effect on the luminescence painting. The model surface temperature during the run was measured in several points with PT100 thermocouples. The maximum fluctuation of the temperature for all measurements was smaller than 2°C. Required accuracy for pressure measurements in the low speed regime must better then 0.1 mbar. For pyren-based PSP formulations this pressure resolution requires 0.05% of relative intensity resolution. Pyren-based PSP formulations has temperature coefficient in the range of 0.3 to 0.5%/°C. Uncertainties of 1°C of the temperature distribution on the model surface will create error about 10 mbar than is significant for low speed measurements. Therefore one of the most important remaining systematic errors for the PSP measurements comes from temperature influences.

Quantum and read-out noise of used CCD camera referred to maximum dynamic range can be estimated as 0.2%. Taking into account that to calculate relative intensity it is necessary to use six images (three: sensitive, reference intensity and dark images for "wind-of" conditions and the same three for "wind-on" conditions) the error of relative intensity will be not less then 0.4%. Thus there are two possibility to improve intensity accuracy measurements: to average appropriate number of each images that is time consuming operation or to use additional spatial filtering that finally reduces spatial resolution. Pressure distribution on the wing model is near one-dimensional that gives possibility to use appropriate spatial filter without significant loss of resolution.

RESULTS

A typical PSP result for the investigated model for U_∞=60m/s, α = 16°is given in Fig. 6. The image in Fig. 6 qualitatively visualizes the pressure distribution over the wings suction side.

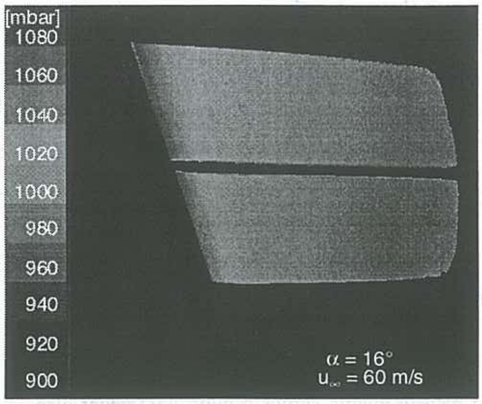

Fig. 6 Visualization of the pressure distribution on the model surface for U_0= 60m/s, α= 16°

The comparison for U_∞= 60m/s, α= 16° in Fig.7 of the measured static pressure values using the PSP technique and the conventional pressure tap technique (PSI) shows already a acceptable agreement.

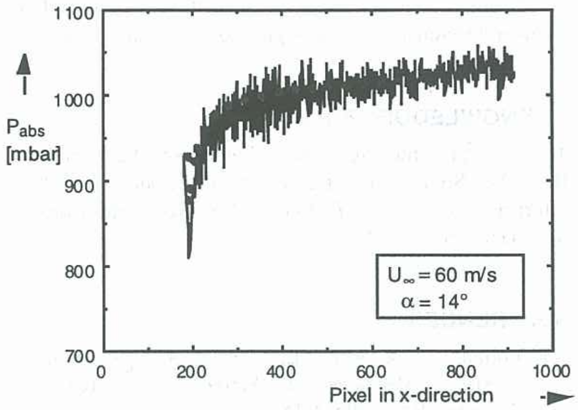

Fig. 7 Comparison of the PSI/PSP pressure distributions on the models suction side surface

The presented comparison in Fig.7 shows rather rough PSP results. This fluctuation gives an impression about the possible SNR of the used PSP setup, for single measurement of "pressure/reference" images. That means that no image averaging method was used to reach an higher SNR.

Because of the more or less one-dimensionality of the pressure distribution on the wing model, it is useful to use a 3 x 3 pixel Gaussian spatial filter. The result of such a approach for the same case than in Fig. 7 is shown in Fig. 8.

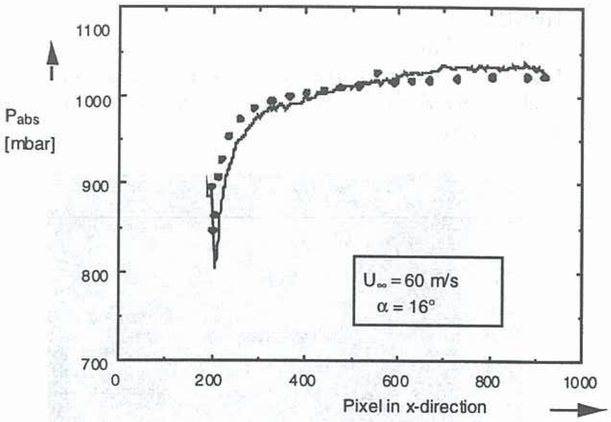

Fig. 8 Comparison of the PSP/PSI pressure distributions on the models suction side surface for U_∞=60m/s, α=16° using spatial filter

The measurements shows a good agreement also for the flow speed of U_∞= 60m/s as well as 40m/s. To minimize the noise a spatial filtering-method was used for the comparison of PSP- and PSI data.

CONCLUSION

Obtained results show that available measurement system can be used for pressure measurements at flow velocities down to 40m/sec. For low-speed measurements the run conditions must be carefully controlled (temperature/dust) and the signal-to-noise ratio must be optimized.

ACKNOWLEDGEMENTS

The here presented tests were funded by the Daimler-Benz AG. Significant contributions to the success of this effort are attributed to P. May and R. Rossmanith (both from Daimler-Benz AG).

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