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Experimental investigation on static/dynamic characteristics of a fast-response pressure sensitive paint

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Abstract An optical-based technique using Pressure-Sensitive Paint (PSP) is a promising method to measure the distribution of surface pressure on an aerodynamic model. The static and dynamic characteristics of a fast-response PSP that is developed in the Chinese Academy of Sciences (CAS) are analyzed and tested to serve as the basis for experiments on unsteady surface measurement using a fast-response PSP. Two calibration systems used for this study are set up to investigate the temperature dependency, response time, and resolution. A data processing method, used for dynamic data, is analyzed and selected carefully to determine the optimum signal. Results show that the fast-response PSP can be used normally at temperatures from 25 °C to 80 °C. The effect of temperature on the accuracy of the measurement must be considered when temperatures are beyond the temperature range of 30–40 °C. The dynamic calibration device with a solenoid valve can achieve a pressure jump within a millisecond order. The resolution is determined by the signal-to-noise ratio of the photo-multiplier tube. Results of the measurement show that the response time of the PSP decreases with a large pressure variation, and the response time is below 0.016 s when the pressure variation is under 40 kPa.
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1. Introduction

Surface pressure measurements are critical to aerodynamic testing in a wind tunnel. However, traditional pressure measurement methods like pressure taps and electronically scanned pressure transducers are poor in spatial resolution and would introduce aerodynamic interference in wind tunnel testing. An optical technique using Pressure-Sensitive Paint (PSP) is a preferred method to measure the distribution of surface pressure on an aerodynamic model. Compared with

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conventional pressure measurement methods, the PSP technique provides a relatively simple and inexpensive method to obtain full-field pressure images of interested surface. Images obtained using the PSP technique have a high spatial resolution and low aerodynamic interference. Thus, the PSP technique has been considered a promising technique in the field of aerospace research.[1]

PSP has been extensively used in steady flow conditions[2–4] with a response time of approximately 1–10 s,[5] which is inconsistent with unsteady measurements. Consequently, several developments have been made to extend the application of PSP to unsteady flows. The USA,[6,7] Russia,[8] the UK,[9,10] Japan,[11–13] and China[14,15] have exerted extensive efforts to develop Fast-response Pressure Sensitive Paints (FPSPs).

Dynamic calibration methods have been developed to determine the response time and response frequency of FPSPs. In response time calibration, a step in pressure is required. Sakaue and Sullivan[16] measured the response time through a successive change of pressure caused by a normal shock wave in a shock tube, and observed the binder thickness and temperature dependencies for the response time. Meanwhile, the solenoid valve has also been used to generate a pressure change for PSP response time calibration.[17,18] In response frequency calibration, a periodic change in pressure is required. Resonance tubes,[13,19] pulsating jets,[20] and fluidic oscillators[7] are capable of determining the applicable frequency range of PSP. Previously published articles indicated that the minimal response time has been pushed to 34.8 μs,[21] thereby satisfying the requirement of unsteady flow measurements.

The Chinese Academy of Sciences (CAS) has developed a fast-response PSP, and its practical application has also been confirmed by testing in a circular cylinder measurement.[22] However, the characteristics of the FPSP are still poorly elucidated. In the current study, the static and dynamic characteristics of the FPSP, including temperature sensitivity and response time, are analyzed to serve as the basis for an experiment on unsteady surface measurement.

2. Measurement principle

PSP techniques are based on photoluminescence (which includes both fluorescence and phosphorescence) and the oxygen-quenching characteristics of a few polymer probe molecules.[23] There are two primary methods for acquiring the pressure data of a PSP: intensity method and lifetime method. The intensity-based (radiometric) method is based on the dependence of the intensity on pressure, and it employs continuous illumination and records the intensity of luminescence from a paint. It has been widely used because of its low requirement of measuring equipment and simple principle. The lifetime method is based on the dependence of the luminescent lifetime on pressure. Due to its high demand for the performance of equipment such as the light source strobe frequency, it is difficult to be applied in continuous measurement. Therefore, the intensity-based method is finally used in this paper.

The pressure and luminescent intensity can be modeled by a simplified form of the Stern-Volmer relation, which can be expressed as[24]

$$\frac{I_{\mathrm{ref}}}{I} = A(T) + B(T)\frac{P}{P_{\mathrm{ref}}} + C(T)\left(\frac{P}{P_{\mathrm{ref}}}\right)^2 + \ldots \tag{1}$$

where I_{ref} represents the intensity of luminescence at the reference, and I represents the test conditions. Their pressure distributions are represented by P and P_{ref}, respectively. $A(T)$, $B(T)$, and $C(T)$ are temperature-dependent calibration coefficients.

3. Characteristics of fast-response PSP

The static and dynamic characteristics of the PSP must be confirmed before applying the fast-response PSP technique to an unsteady flow field measurement. In particular, the static characteristics refer to the temperature and pressure dependencies, while the dynamic characteristics include the response time and frequency. Limited by experimental equipment, we do not study the frequency characteristic of the paint. A brief description of the paint and these characteristics will be presented in this section.

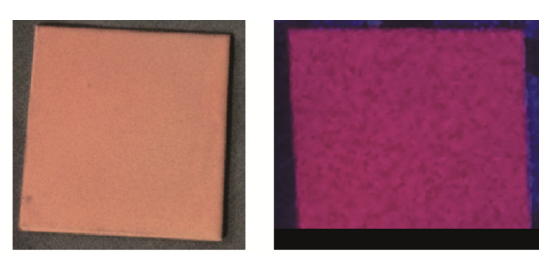
3.1. Description of fast-response PSP

The fast-response PSP used in the current study is developed in the China Academy of Aerospace Aerodynamics (CAAA) and the Institute of Chemistry Chinese Academy of Sciences. The PSP is excited by a generated light of an LED array centered at 365 nm (approximately 20 nm full width at half maximum), which is the optimal excitation wavelength. The emission light of the PSP is from 600 nm to 700 nm. The plate colors of the PSP sample before and after excitation are shown in Fig. 1, in which an orange plate color is observed before excitation and a fluorescein red after excitation. By attaching a luminophore to the porous binder, the contact area between the luminophore and an oxygen molecule is substantially increased, thereby decreasing the response time.[25]

3.2. Static characteristics

Pressure changes are correlated with the changes of temperature. To ensure the accuracy of a measurement, the effect of a temperature change on fast-response PSP results must be considered. Temperature sensitivity S_{T}, which is expressed in %/100 K, is defined to analyze the temperature effect intuitively, which is expressed in Eq. (2). It is a mean value of luminescent intensity in the temperature range of T_1 to T_2. I_1 and I_2 are the intensity of luminescence at T_1 and T_2 respectively. High temperature sensitivity indicates high temperature errors, which is not what we expect.

Another important static characteristic that should be considered is pressure sensitivity S_{p}, which is expressed in %/100 kPa and has a very similar definition to temperature sensitivity, and their expressions are shown as follows:



(a) Unexcited PSP sample plate (b) Excited PSP sample plate

Fig. 1 Colors of fast-response PSP before and after excitation.

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