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Pressure Measurement on Suction Surface of a Single Vane Using Pressure-sensitive Paint

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Abstract

Global pressure distribution on the suction surface of a single vane in a transonic cascade wind tunnel is measured with the help of intensity-based pressure-sensitive paint (PSP) technique using a type of temperature-insensitive fluorescent paint and a self-made measurement system. This measurement is conducted at the outlet of the cascade wind tunnel at the Mach numbers 0.3 and 0.4, attack angle about –20°, ambient pressure 95.4 kPa and temperature 15 °C. The vane under study owns a large camber angle of about 40° and 4×10 pressure ports on its suction surface with a steel cubic stand attached. It is fixed vertically on the lower guide steel plate at the outlet through the stand for convenient acquisition of images. Conventional electronic static pressure (ESP) measurement is also fulfilled simultaneously with an ESP scanner for comparison. The method of intensity-based PSP technique is introduced, especially, with the self-made PSP system. The operating sequence of PSP measurement for improved accuracy is also proposed. The practical steps of image processing are described. As an image registration, target alignment is introduced after the 4×10 pressure ports have been selected as targets. The comparison of PSP results with ESP data shows that the maximum error remains within 6.5%.

Keywords: turbomachinery; pressure measurement; pressure-sensitive paint; pressure distribution; cascade wind tunnel; suction surface of vane; image registration

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1. Introduction

Pressure measurement on blade surfaces by using the pressure-sensitive paint (PSP) has been advancing rapidly these years. It is because of its unique advantages such as the absence of intruding measured surfaces, application of image processing to acquire global pressure distribution, and the acquisition of PSP results that traditional methods could never obtain[1-6]. Several scientific and technological institutes and research groups have made remarkable contribution to PSP applications. The Central Aero-Hydrodynamic Institute (TsAGI) in Russia and NASA in U. S. have applied a series of PSP to various industry wind tunnels inclusive of subsonic, transonic, supersonic and shock wind tunnels as well as turbomachines. Especially, the researchers like J. Lepicovsky, et al. in TsAGI[7-8], T. Liu, et al. at NASA's Langley Research Centre[9-12], and T. J. Bencic at NASA's Lewis Research Centre[13] have carried out several noticeable work relevant to stationary and rotating fan blades.

Although the advances in PSP are of great significance and use, the effects on measuring accuracy out of changing illumination on measured surfaces, inconsistent thickness of paint coatings, and their sensitivity to temperature, detectors' noise, relative motions of the model of interest, and noise from image processing must be carefully investigated before establishing a PSP measurement system. For the intensity-based PSP technique, intensity ratio of a pressure (wind-on) image to the reference (wind-off) image is of great importance to understand the pressure distribution on measured surfaces. The application of intensity ratio method is able to suppress or even eliminate the above-mentioned effects on PSP measurement accuracy, although much more rigorous presuppositions and limits have to be imposed[14-18]. However, it is convenient for rigid model of interest to satisfy such strict limits when relative motions of the model are so small

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that they could be corrected by image registration.

So far, the PSP measurements have found fewer uses in internal flow field than in external flow field, and there is no information about pressure measurement on suction surfaces of vanes in a transonic cascade wind tunnel. As a trial, the pressure measurement on a single stator vane by way of PSP technique was conducted with a kind of fluorescent temperature-insensitive PSP and a self-made PSP measurement system at the outlet of a transonic cascade wind tunnel. Another traditional pressure measurement with a set of electronic static pressure (ESP) scanners was also taken with 10 columns of ports on the vane suction surface for the purpose of comparison. Post calibration was introduced to avoid disagreement between reference pressure during experiment and in calibration. Image registration was used to match the pixel positions of a vane in pressure and reference images. Comparisons of PSP pressure distributions with static pressures of the ports are helpful to attain an acceptable agreement.

2. Comprehensive Overview of Intensity-based PSP Technique

For the intensity-based technique, the Stern-Volmer relation serves to be the base, which can be defined by the following second-order derivative equation:

$$\frac{p}{p_{\text{ref}}}=A(T)+B(T)\left(\frac{I_{\text{ref}}}{I}\right)+C(T)\left(\frac{I_{\text{ref}}}{I}\right)^2 \tag{1}$$

where the Stern-Volmer constants $A(T)$, $B(T)$ and $C(T)$ are determined in the postcalibration as a function of ambient temperature T; the variables p and I stand for pressure value and gray level of luminance intensity produced by PSP, and the subscript “ref” means for reference only.

The preconditions for application of PSP technique are very strict that they are often regarded as a representative of the ideally perfect conditions, which could never be met in practice, for example, uniform luminance on measured surfaces of model, consistent thickness of paint coatings, even distribution of temperature on measured surfaces, absence of relative motion in position during operation, and ideal emission without spectral variability and filter leakage and the rest.

However, the above restrictions can be removed practically by applying a ratio of a pixel of an image to that of another measured one via choosing an ideal PSP with lower temperature sensitivity and good pressure sensitivity, using various means to maintain the pixel position of reference and pressure images unchanged in a uniform image coordinate system or, at least, pixel positions of model pictures equal to each other and so on.

The Stern-Volmer relation derivative, Eq.(1), can be considered valid under perfect conditions and there being only one pixel. For home-made temperature-insensitive paint, the temperature distribution on the measured surfaces can be ignored when below 40 °C. The arithmetical averages of images’ intensity under diverse pressures in calibration are generally accepted as a significant fundamental relation of intensity-ratio in pressure data conversion without any relative motions, which can be denoted by

$$\frac{p}{p_{\text{ref}}}=A_{\text{ave}}(T)+B_{\text{ave}}(T)\left(\frac{I_{\text{ref}}}{I}\right)+C_{\text{ave}}(T)\left(\frac{I_{\text{ref}}}{I}\right)^2 \tag{2}$$

where $A_{\text{ave}}(T)$, $B_{\text{ave}}(T)$, and $C_{\text{ave}}(T)$ stand for the averages of Stern-Volmer constants respectively, determined in calibration, and the subscript “ave” means the average value.

In the basic theory of Image Processing, an image can be viewed as an array of pixels called an image matrix, which indicates the diversified gray levels of luminance intensity in an image and, thus, Eq.(1) can be rewritten into

$$\frac{\boldsymbol{p}}{\boldsymbol{p}_{\text{ref}}}=A_{\text{ave}}(T)+B_{\text{ave}}(T)\left(\frac{\boldsymbol{I}}{\boldsymbol{I}_{\text{ref}}}\right)+C_{\text{ave}}(T)\left(\frac{\boldsymbol{I}}{\boldsymbol{I}_{\text{ref}}}\right)^2 \tag{3}$$

where the symbol $\boldsymbol{p}$ denotes an image matrix of pressure and $\boldsymbol{I}$ another one of intensities; “ref” the wind-off or reference condition in experimental measurements.

The data conversion from intensity-ratio to pressure distribution can be carried out through Eq.(3) with the known Stern-Volmer constants $A_{\text{ave}}(T)$, $B_{\text{ave}}(T)$ and $C_{\text{ave}}(T)$, determined in calibration under the supposition of none of motion that has occurred.

The relative motion of model of interest may be caused by irregular and inherent vibration of test facilities in operation and exerts alternating steady and/or unsteady aerodynamic loads on the model of interest, which would aggravate the variation of illuminance on the measured surface of model and hence incite alternating effects on luminance intensity of measured surfaces in the case where there are none of uniform light emission and consistent thickness of PSP coatings. To remedy this, image registration is introduced to abate the inaccuracy by mapping the deformed pressure image coordinates $(\boldsymbol{x}, \boldsymbol{y})$ onto the reference images coordinates $(\boldsymbol{x}_{\text{ref}}, \boldsymbol{y}_{\text{ref}})$. The generalized equation for image registration of image matrices with an $n\times n$ array could be expressed by

$$\left.\begin{aligned}\boldsymbol{x}_{\text{ref}}&=\sum_{i,j=1}^{n}a_{ij}f_i(\boldsymbol{x})f_j(\boldsymbol{y})\\ \boldsymbol{y}_{\text{ref}}&=\sum_{i,j=1}^{n}b_{ij}f_i(\boldsymbol{x})f_j(\boldsymbol{y})\end{aligned}\right\} \tag{4}$$

where both basic functions $f_i(\boldsymbol{x})$ and $f_j(\boldsymbol{y})$ are the orthogonal functions or the nonorthogonal power functions $f_i(\boldsymbol{x})=x_{\text{c}}$ or $f_j(\boldsymbol{y})=y_{\text{c}}$ with c being a constant value. Given the image coordinates of the black targets