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PRESSURE DISTRIBUTION MEASUREMENT OF IMPINGING JET ON A SINGLE STATOR VANE EMPLOYING PRESSURE-SENSITIVE PAINT

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Abstract

Pressure-sensitive paint (PSP) technique has been more and more popularly applied in industrial fields because of its unique advantages such as high cost-efficiency, time-saving preparation, and convenient operation. Investigation on characteristics of PSP formulation plays an essential and primary role in research and industrial application. Impinging jet supplies an effective access to certify and validate the feasibility of PSP recipe on research and industrial purposes as well as its potential application prospective. Pressure measurement, which demonstrated the resolution capability of pressure gradient along the vane surface, has been conducted with high pressure air jet impinging on a single stator vane based on self-established measuring system and in-house paint formulation. The fact that obtained pressure distribution images of jet impinging visually displayed the pressure gradient on vane

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suction surface indicated the resolution property on pressure change except for distinct inaccuracy resulting from narrower calibration pressure range for broader application regime. A qualitative examination of response time was also conducted by fast CMOS camera, which shows potential capability of fast response to pressure variation.

1. Introduction

Pressure-sensitive paint (PSP) technique has become an advantageous and promising measuring technology in various fields such as aeronautics, astronautics, turbomachinery, and aerodynamics, which has been improved in industrial level of application since 1980's. Quite a few research institutes and universities in developed nations have conducted relevant exploration and investigation for more than two decades. The fact that PSP measurement systems have been equipped in their diverse wind tunnels and other testing facilities indicates the industrial level of PSP application [3-5, 7, 9-12]. And several academic institutes in developing states stared their works on PSP at the end of last contrary, and have acquired interesting and dramatic contributions. Nowadays, PSP technique is developed as a technical system composed of intensity-based method, lifetime-based approach, and fast-response measure and so on, in which the lifetime-based approach consists of several particular ways with more complicated and sophisticated hardware and fast-response measure contains unique mechanism different from the others. Thus, intensity-based method is more popular than the other ones because of simplicity and convenience in operation [7]. On the whole, advantages of PSP technique have promoted its application in wind tunnels and similar testing facilities, including higher cost-efficiency, distinct time-saving preparation, notable capability of spatial resolution, and convenience for pressure distribution measurements at specific positions with difficulties in deploying orifices or pressure tapes. Even though acting as qualitative flow visualization tool, PSP technique enables to provide more information on the flow field near substantial surface such as bubbles in laminar boundary layer, flow separation and reattachment, vortex development and breakdown, interaction between shockwave and boundary layer etc.

Impinging jet experiments usually imply profound application background for industrial engineering, especially in fields of aeronautics, astronautics, and turbomachinery [1, 2, 6, 8]. Experimental testing of impinging jet on flat plane could additionally supply an access for examine the capability to determine pressure gradient existed, by which investigators can obtain intuitionistic impression and operation experience via impinging jet tests, and establish the relationship of luminescent intensity versus pressure value, known as *Stern-Volmer relation*, in broad pressure range so as to examine signal-to-noise-ratio of obtained images at minimum luminescent intensity corresponding to maximum pressure. Therefore, PSP application on impinging jet could be considered as useful complement to check the possibility applied in broader pressure range.

Testing of 0.6MPa absolute pressure impinging jet employing assembled measuring system and in-house paint formulation of single component pressure-sensitive paint was conducted via intensity-based method with the purpose of examination for in-house characteristic resolution capability of sharp pressure gradient. Experimental model was a straight stator vane with PSP coating over suction surface. The incident angles were 30º, 45º, and 60º, respectively, in which the jet at incident of 60º was almost parallel to the normal of impinging local area. The luminescent images were acquired by assembled acquisition system, and the processed results showed precious capability to distinguish sharp pressure graded distribution in broader pressure range.

2. Fundamental Mechanism

PSP technique is based on photoluminescence including both fluorescence and phosphorescence. The molecules with photoluminescence capability are named “probe molecules”. Being promoted to the excited electronic states of higher energy than ground electronic state by absorbing photons with appropriate frequencies, the probe molecules tend to lose excess energy and return to ground state via multiple approaches such as emitting visible light with longer wavelength, photoluminescence, or transferring excess energy to bi-atomic molecules, quenching. Oxygen is the most popular molecule existed in atmosphere, acting as "quencher". The luminescent intensity is usually inverse proportional to the oxygen concentration, which is direct proportional to the one in atmosphere, inside the PSP coating layer. Since the partial concentration of oxygen among atmosphere is a constant, around 21%, the numeric relationship of luminescent intensity versus local pressure on the coating surface, which is documented as Stern-Volmer relation, depicted as

$$\frac{I_0}{I} = \frac{\tau_0}{\tau} = 1 + K_{SV}P, \tag{1}$$

where I and τ stand for the intensity and lifetime of luminescence, respectively, and the latter is often used for the time-resolving approach among PSP technique; K_{SV} for the Stern-Volmer constant during the excited probe molecules transfer their excess energy and return to the ground electronic state; P for local pressure, and the subscript "0" for the environment without oxygen. However, Equation (1) is not feasible for practical operations. Thus, a reference condition is introduced into Equation (1) to acquire derivative of Stern-Volmer relation as follow:

$$\frac{I_{ref}}{I} = \frac{\tau_{ref}}{\tau} = A(T) + B(T)\frac{p}{p_{ref}}, \tag{2}$$

where $A(T)$ and $B(T)$ are coefficients determined by paint calibration in various temperature conditions, respectively, additionally with the relation of $A(T) + B(T) = 1$; the subscript "ref" stands for the environment condition chose arbitrarily, usually local atmosphere condition for convenience. Equation (2) has been employed for two times. At first, paint calibration is used to determine the values of $A(T)$ and $B(T)$ at relevant conditions. At last, luminescent intensities over the coating surface are transferred into the pressure values normal to the local area of coating surface. Since PSP is both pressure and temperature sensitive, it is quite difficult to correct the temperature sensitivity of PSP in order to promote the measurement accuracy.

3. Paint Formulation and Assembled Measuring System

The PSP formulation employed was an in-house paint of single pressure sensitive component developed by Chemistry Institute of Chinese Science Academic. Its excitation spectrum ranges from 320nm to 390nm with optimum absorbing bound of 320nm to 340nm. The emitting wavelength varies from 485nm to 525nm, blue light in visible spectrum. PSP coating consists of two layers, which both are applied via air brush; the prime coating is white and acts as a reflector to enhance both intensity of excitation light and emitting luminescence, while the upper layer is functional coating containing probe molecular or luminophor. The thickness of each layer is around 20 to 40 micron, thus total thickness reaches 40 to 80 micron. The temperature sensitivity of the PSP employed is so considerable low that, it can be treated as insensitive paint, named "ideal pressure sensitive paint".

PSP measurement system is essential and elemental instrumentation for PSP applications, which was assembled with CCD cameras from particle image velocimetry (PIV), a continuous light source with broad spectrum, controlling and triggering module as well as calibration chamber with pressure adjustment and controlling unit connected to air compressor and vacuum pump, respectively. The light source was a substitute, which is initially used as curing system, which can emit high illumination of 0.5 watt per cm^2 in UVA spectrum at the distance of 60mm away from the naked lamp head. Several low pass filters were introduced in front of the light source, and thus, a small filter cabin was designed to fix the filters and a piece of coarse quartz glass for mitigating the non-uniform illumination of the light source in cost of decreasing excitation light intensity. An aeration access was prearranged inside the cabin for reduce the internal temperature as well as the temperature along filter surface. Two CCD cameras are designed with spatial resolution of 1600×1200 responding to the pixel size of 7.4 micron and dynamic gray regime of 10 bits and without cooled function. The maximum of pressure range for calibration varies from 10KPa to 250KPa.

The calibration unit consists of a chamber enable to sustain vacuum and pressure of 600KPa, a manual adjusting valve, a barometer with high accuracy as well as some pipes. The chamber has a visible window composed of 20mm thick organic glass (PMMA) and a steel flange to fix PMMA with three or six long screws.

4. Set-up for Impinging Jet Measurement

The set-up of impinging jet measurement is displayed in Figure 1. The base is a piece of wooden floor plate with a cuboid wooden block of about 15cm mounted on it. A piece of brass pipe of around 10mm diameter passes through the block. The angle between the centre line and the base plate was set at 30º, 45º, and 60º, respectively. An end of the pipe was connected with polyvinyl pipe, which was linked to the outlet of air compressor. The maximum pressure at its outlet can reach at 0.6MPa (absolute). There is no pressure adjustment along the pipes. The vane with its suction surface coated was placed on the base plate via polyvinyl sticking strip binding its both ends, thus, the suction surface was just above the intersection of the brass pipe and base plate. The excitation light source together with the filter cabin was above the vane near normal of the base plate, and a scientific grade CCD camera was parallel to the light source with an angle of 45º to the normal of base plate. The photograph of experimental arrangement is shown in Figure 2.

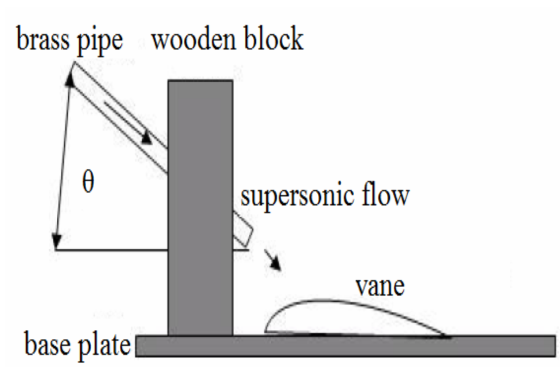

Figure 1. Schematic of impinging jet set-up.

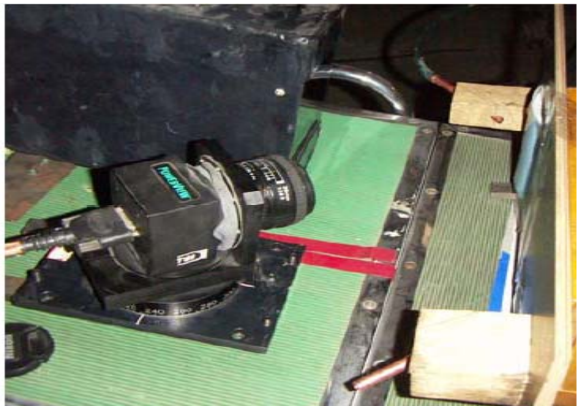

Figure 2. Photograph of experimental set-up.

In experimental measurements, the triggering of supersonic flow inside the brass pipe and the control of image acquisition were both in manual operation. Since there is none pressure adjustment in measurements, high pressure jet impinging on the suction surface is actually a dynamic process, especially at initial and last stages. Therefore, more than 50 images have been caught during impinging process for each run. There are about three runs for each impinging angle. More than 20 reference images have also been acquired before and after each run. There is none marker point on the suction surface since the vane was fixed firmly on the base plate, corresponding to vane translation of less than two pixels in images. About 20 dark background images have been caught before each run.

5. Image Processing and Results Analyses

Image processing should be conducted after experiments to acquire qualitative or quantitative distribution images, which is composed of dark current subtracting, image average, image smoothing, and image registration etc. The processes of image processing were conducted for each run with dark current images, reference images at wind-off and experimental images at wind-on conditions, which were proceeded according to the procedure as follows for each run:

1. Images caught at wind-on and wind-off conditions during experiments were subtracted by dark background image, respectively.

2. The subtracted images at wind-on or wind-off conditions were averaged, respectively, and since there was none translation shift in experiments, image registration was no longer needed.

3. Ratio calculations of images at wind-off to wind-on was conducted, processes of median filtering and image smoothing were followed to suppress the noise induced by ratio calculation.

4. Stern-Volmer relationship was established via paint calibration though experimental pressure range exceeded that for calibration.

5. Gray level range of ratioed images was appropriately adjusted to eliminate the additional noise resulted from ratio calculation.

6. Transformation from intensity to pressure values was then employed for quantitative pressure distribution by means of dedicated processing software package and processing procedures based on Matlab code.

Pressure distributions on vane suction surface at various impinging angles have been acquired and are shown in Figure 3 to Figure 5 via false-colour style. The area of high speed and low pressure is clear in these images and so is zone of the low speed and high pressure. There exist large high speed and low pressure area behind the impinging point on the vane suction surface, where locate a large expansion zone both since the curvature of vane and intrinsic expanding behind the impinging point similar to the situation on flat plate. The flow fields near suction surface of the vane were not detailed for lack of Schlieren technique, which was not the main object of this investigation. It is interesting that the jet impinging on the vane suction surface may be more complicate than on flat plate. Even more, the fact that variation in colour shows the sharp pressure change demonstrates the pressure resolution of PSP clearly and vividly, and also that compromise between the detail and the perspective should be chosen for different purpose because of the limitation on false-colour display style. The jet at impinging on vane at the angle of 60º near the leading edge of the suction surface was similar to the situation on flat plate at the angle of 90º because of curvature of the vane. That is similar to the situations for the jet impinging at 30º and 45º .

It should be mentioned that, the actual pressure regime in measurements was so larger than the range in calibration that extrapolation had to be used in transformation of intensity to pressure. Also, since Stern-Volmer relationship acquired via calibration is non-linear, usually quadratic polynomial, there must be dramatic error of extrapolation in transformation. The other reasons for possible measurement error may results from the intrinsic temperature sensitivity of in-house PSP employed. The images from Figure 3 to Figure 5 are not global distributions on the vane because of the purpose for this investigation.

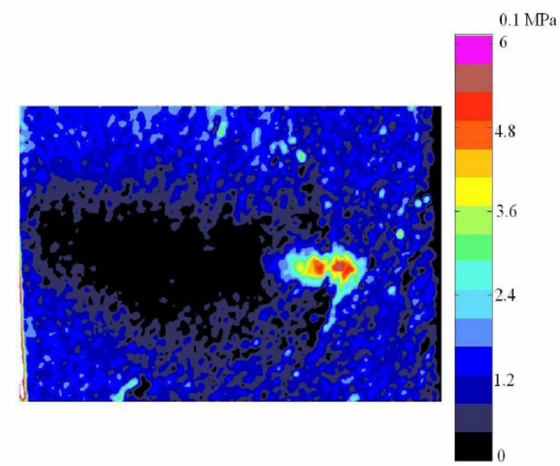

Figure 3. Pressure distribution of high speed jet impinging at the angle of 45º.

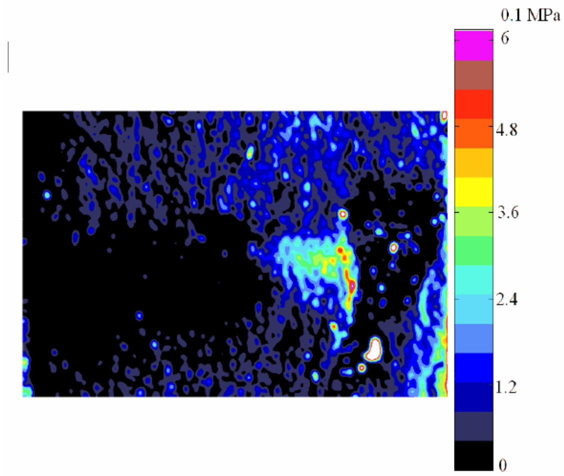

Figure 4. Pressure distribution of high speed jet impinging at the angle of 30º.

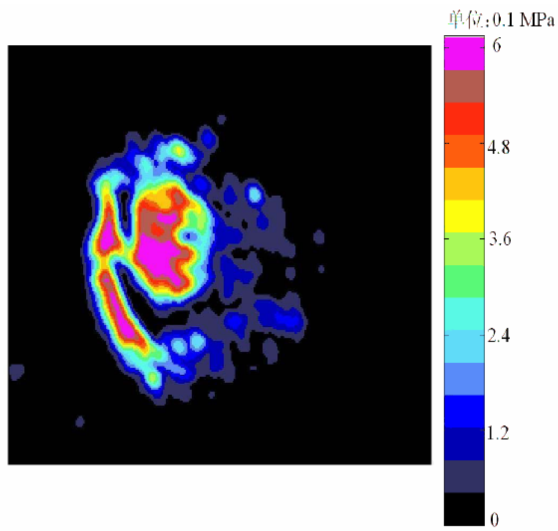

Figure 5. Pressure distribution of high speed jet impinging at the angle of 60º.

Attempt to demonstrate the temporal response of in-house PSP by a fast CMOS camera with a rate of 6000 frame per minute. It is estimated that the response time of in-house PSP reaches 10 millisecond at most. Thus, the temporal response of the in-house fluorescent PSP approaches the least requirement for of fast response PSP. Further examination should be under investigation for more convictively quantitative certification testing.

6. Conclusion

A series of demonstration tests have been conducted to certify the pressure resolution of in-house fluorescent PSP with assembled PSP measurement system via high pressure jet impinging on a coated straight stator vane suction surface. Experimental set-ups were designed at 30º, 45º, and 60º according to the angle of the jet centerline to the base plate fixed with jet pipe. The pressure distribution images were acquired with images caught in experiments via image processing method, which showed the resolution potential to the pressure gradient on the coated suction surface for future PSP applications. Additionally, the temporal response of in-house PSP was examined qualitatively with fast CMOS camera, which indicated that its response time approaches the least requirement for the fast response PSP. Further investigation needs to examine the more details.

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