

EVALUATION AND VALIDATION OF PSP AND TSP MEASUREMENT TECHNIQUES IN TURBOMACHINERY APPLICATIONS

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ABSTRACT

This work details the development and application of fast-responding pressure-sensitive paint (fast PSP) and temperature-sensitive paint (TSP) for measuring unsteady surface pressure and temperature on fast rotating blades of turbomachinery. Two measurement techniques: phase-lock intensity-based method and single-shot lifetime-based method were first performed on a high-speed fan and the results were evaluated and validated. The single-shot lifetime-based method was found more suitable for measurements of fast rotating blades. Therefore, an experiment using single-shot lifetime-based method was carried out on a turbocharger compressor using the testing facility at Wuxi IHI Turbo (WIT). The pressure distribution on the compressor blades were compared between numerical simulation data and experimental results. The PSP and CFD data showed good agreement in most regions.

INTRODUCTION

Turbomachinery is widely used in industry as energy conversion devices like compressors and gas turbines. Due to the high rotation speed and complicated mechanical structure, the flow field in a turbomachine is complex and unsteady, especially working under off-design conditions. There is a growing interest in measurements of turbomachinery internal flow field in recent years, which helps understand the flow

mechanism and improve the design or control schemes. However, it is difficult to conduct flow field measurements with high spatial resolution using conventional methods due to the high rotation speed and complex geometry of the rotors. Miniature semi-conductor pressure sensors¹ and thin-film sensors² were developed for rotating blades applications, however, limited flow field information was obtained due to the low spatial resolution. Fast PSP and TSP³ are optical techniques that enable non-contact, high-resolution surface pressure and temperature measurements, which could provide valuable flow field information. It is feasible to carry out a detailed measurement of surface pressure and temperature on rotating blades.

A main challenge to conducted PSP/TSP techniques to fast rotating surface is developing a proper image acquisition system to record high quality PSP/TSP emission signals. In previous study, phase-lock method^{4,5} and single shot method^{6,7} were adopted by several researchers for measurements of rotating surfaces. However, these two methods were still not fully compared and evaluated in previous studies. In the current study, PSP/TSP technique was applied to measurements of aerodynamic parameters on fast rotating blades using two data acquisition methods: phase-lock intensity-based method and single-shot lifetime-based method. The experiment was first conducted on a high-speed fan. Results and characteristics of these two methods were compared and evaluated. The single-shot lifetime-based

method was found to be more suitable for turbomachinery applications. Based on which, a measurement of surface pressure and temperature on turbocharger compressor blades was carried out using single-shot lifetime-based method. The flow field obtained by PSP measurement was validated and evaluated by a comparison with CFD data and the results showed good agreement in most regions on the test blade.

METHODOLOGY

1. Phase-Lock Intensity-Based Method

The principle of PSP/TSP technique is based on the inversely proportional between luminescence intensity and local oxygen concentration or temperature due to the oxygen quenching and thermal quenching of excited luminescent molecules. Pressure values could be computed by Stern-Volmer equation³ using the PSP/TSP image data acquired at test and reference conditions. It is challenging to obtain good quality PSP images of fast rotating surfaces due to short exposure time of image acquisition devices and limited power of the excitation light source. Phase-lock method provides a feasible way to apply PSP/TSP techniques on fast rotating surfaces. In this method, the CCD camera is allowed to acquire the luminescent signals of the PSP coating at the same rotation phase in multi revolutions. The signals are accumulated automatically by the CCD chip. Finally, a PSP/TSP image with high signal to noise ratio (SNR) would be obtained

The schematic and system timing of phase-lock system is shown in Figure 1. In the experiment, TTL signals were generated by an optical sensor at a certain rotation phase. The original phase signals were delayed to the test rotation phase by a delay generator. Then the processed signals were used to trigger the pulsed UV laser. As a result, PSP paint on the test blade was excited at the same rotation phase. The shutter of the CCD camera was kept open for a long time to capture luminescent signals excited by a number of laser pulses. In this way, the PSP/TSP signals at the same rotation phase were accumulated by the CCD chip and a good quality PSP/TSP image was obtained.

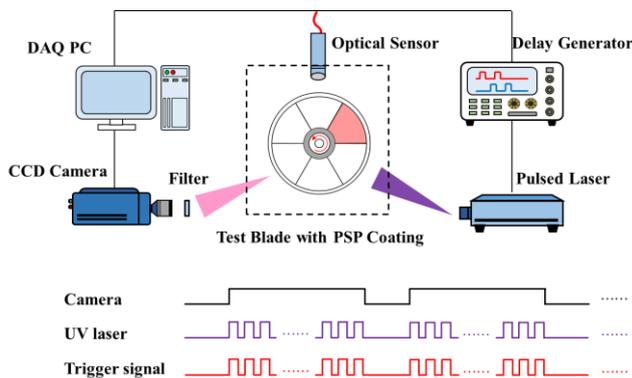


Figure 1 Schematic and system timing of phase-lock intensity-based method

2. Single-Shot Lifetime-Based Method

Gregory et al.⁶ proposed a single-shot lifetime-based PSP technique. In this method a pulsed laser was used to excite PSP coating. High SNR images could be captured using this

method without any phase-averaging due to the high power of laser light source. Additionally, using short width pulsed excitation light could reduce motion blur in PSP images of moving surface. This method has been successfully used for PSP measurements of turbocharger compressor blades⁸.

Figure 2 shows the schematic of the two-gate image acquisition approach in this method. When the PSP coating was excited by a pulsed laser, a CCD camera was used to take two consecutive images within one excitation cycle. The image of Gate 1 contained the initial portion of the decay curve servers as a reference due to the relatively insensitivity to pressure. Gate 2 covered the most of the luminescent decay which had more pressure sensitivity. The pressure information could be obtained from the intensity ratio of two gated images which was dependent to the luminescent lifetime.

In order to reduce the errors due to paint inhomogeneity, a ratio of ratios method⁹ was applied in the image processing. An intensity ratio between two gates at reference condition was used to eliminate the spatial variations in lifetime. The modified Stern-Volmer equation for single-shot lifetime-based method is

$$\frac{(I_2/I_1)_{ref}}{I_2/I_1} = A(T) + B(T) \frac{p}{p_{ref}} \quad (1)$$

where I_1 and I_2 are intensities from Gate 1 and Gate 2, respectively. The Stern-Volmer coefficients A and B , which were temperature-dependent due to thermal quenching, were experimentally determined by calibration.³ The schematic of the data acquisition system for single-shot lifetime-based method is shown in Figure 3.

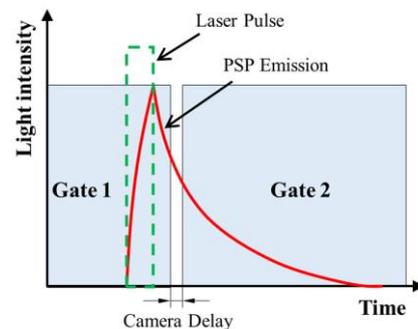


Figure 2 Data acquisition of single-shot lifetime-based method

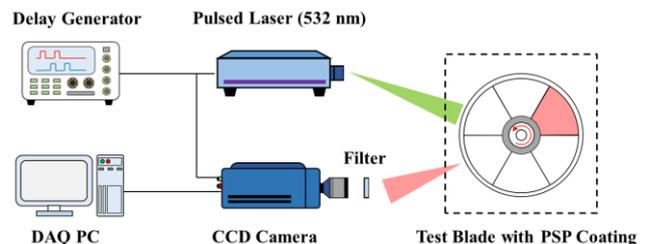


Figure 3 Schematic of single-shot lifetime-based method

EXPERIMENTAL SETUP

The evaluation and validation experiments were firstly conducted on a high-speed fan using both single-shot lifetime-based method and phase-lock intensity-based method. The ducted fan had diameter of 70mm with a 6-blade impeller which was driven by a 12V electric motor. The measurement was conducted at 5k rpm, 10k rpm, 15k rpm. As shown in Figure 4, three separated blades were painted: one blade was painted with TSP and the other two blades were painted with PSP.



Figure 4 The high-speed fan painted with PSP and TSP

In the experiment, a 532nm Nd: YAG pulsed laser (pulse width: ~ns) was used as excitation light source and it was triggered by a TTL rotation phase signal produced by a Monarch Instruments ROS-5W optical sensor and processed by a BNC 575 delay generator. A PCO 1600 14-bit CCD camera mounted with a Nikon f/2.8 60-mm lens and a 590nm long-pass filter was used to capture PSP/TSP images.

The experiment using single-shot lifetime-based method was carried out on a turbocharger test bench at WIT. The turbocharger was powered by compressed air and the rotation speed ranged from 30k rpm to 120k rpm. The impeller, with a diameter of 40mm, had six main blades, as shown in Figure 5, including two blades painted PSP and one blade painted with TSP. These three blades were not adjacent to each other to avoid possible interference effects during image deblurring. The turbocharger rotor was installed on the test facility after fabricating the PSP/TSP coating. After a dynamic balance test, the turbocharger rotor operated safely under test conditions: 60k rpm, 90k rpm and 111k rpm.

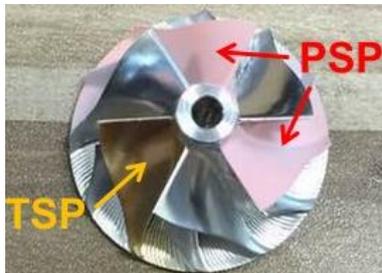


Figure 5 PSP/TSP coating on the test blades

The experimental setup of single-shot lifetime-based method is shown in Figure 6. The same 532nm pulsed laser, CCD camera, lens and filter as the experiment of the high-speed fan were used as excitation and image acquisition devices. The CCD camera worked in double-frame mode. The system timing was controlled by a BNC 575 Delay generator. In the experiment, the exposure time of Gate 1 is 5 μ s. The

length of Gate 2 is determined by the camera which is much longer than the decay lifetime of the paint.



Figure 6 Experimental setup of single-shot lifetime-based method

DATA PROCESSING

The data processing procedure of phase-lock intensity-based method is shown in Figure 7. The signal in each image contained the luminescence signals responded to the same number of laser pulses. Due to the short nanosecond laser pulse width, the motion blur in each wind-on image was so slight that the wind-on image could be directly used to compute the intensity ratio pixel by pixel with a wind-off image. Then the intensity ratio result was calibrated to pressure and temperature data using the calibration results. In the high-speed fan experiment of Figure 4, only the pressure ratio field was computed without calibration and subsequent processing, due to the poor quality of the images.

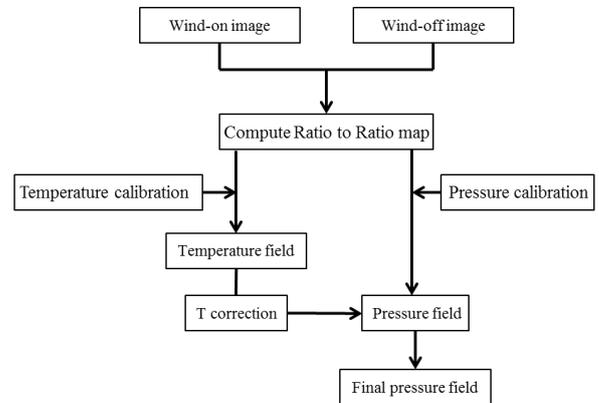


Figure 7 Data processing procedures of phase-lock intensity-based method

The data processing procedure of single-shot method was described in detail in Peng et al.'s work^{8,10}. There were four main steps in the current data processing method: coordinate transformation, image deblurring, image registration and temperature correction. The first step was to transfer the images from cartesian coordinate to polar coordinate using an image transformation algorithm¹¹. A deconvolution-based image deblurring technique^{12,13} was performed to reduce the motion blur due to the high rotation speed.

The temperature field was obtained using the temperature calibration curve, as shown in Figure 8, which is obtained using a calibration system. For pressure field, a correction was

needed to remove the temperature induced errors due to the pressure sensitivity of PSP. The method was conducting temperature calibrations of PSP under different pressures, the results are shown in Figure 9. At each pixel, the temperature value was already obtained by TSP. The ratio of ratios of different pressures at this temperature was used to fit a pressure calibration curve, using which, pressure values was computed pixel by pixel and the pressure field on the test blade was obtained.

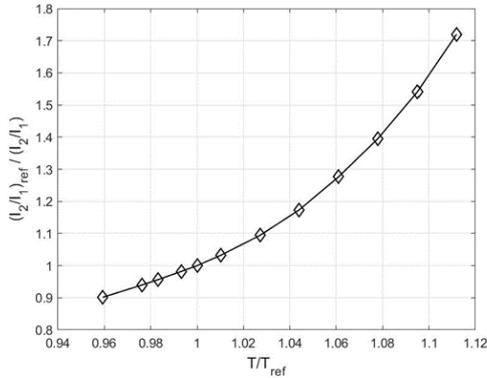


Figure 8 Temperature calibration result of TSP

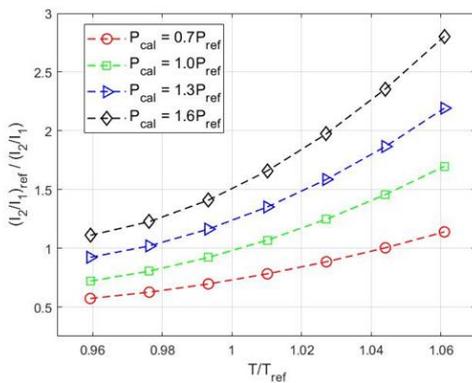


Figure 9 PSP calibration results under different pressures

RESULTS AND EVALUATION

1. Results of high-speed fan experiment

In the phase-lock intensity-based method, the PSP signals in responded to multiple laser pulses was accumulated and merged in one image. Figure 10 shows the PSP images obtained by using different numbers of laser pulses. Clearly, the signal intensity enhanced with an increasing number of laser pulses. The phase-lock intensity-based method provided an effective way to enhance the SNR by increasing the number of laser pulses within the acquisition time of each image. Essentially, the phase-lock intensity-based method was a time averaging method that enhanced the SNR at the expense of the temporal resolution.

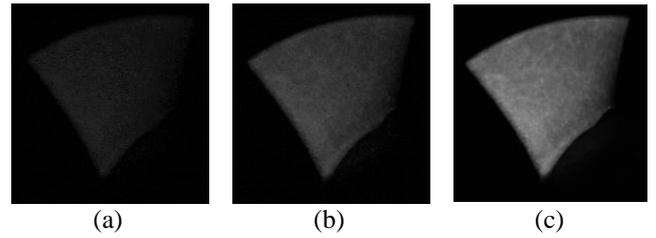


Figure 10 PSP images of (a) 20 laser pulses, (b) 50 laser pulses, (c) 100 laser pulses

The intensity ratio was computed using wind-on and wind-off images obtained at 10k rpm, 100 laser pulses were accumulated in each image. As shown in Figure 11, the I/I_{ref} intensity ratio map is very rough and full of large-scale speckles. This problem was caused by the properties of the laser light source. The 532nm Nd: YAG pulsed laser used in this experiment had a spatial mode structure. The spatial energy distribution of each laser shot was not uniform, and the speckle pattern varied from shot to shot. In the phase-lock intensity-based method, emission signals of wind-on and wind-off were excited by different laser pulses. The speckle pattern could not be counteracted even though multiple pulses were accumulated in each image. Therefore, the laser-based phase-lock method has a high requirement to the excitation light source, a pulsed excitation light source with short pulse width and uniform spatial energy distribution is need.

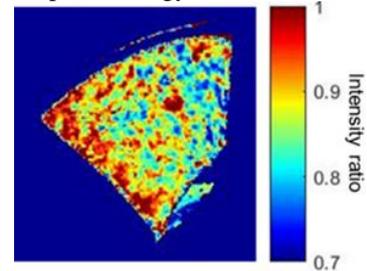
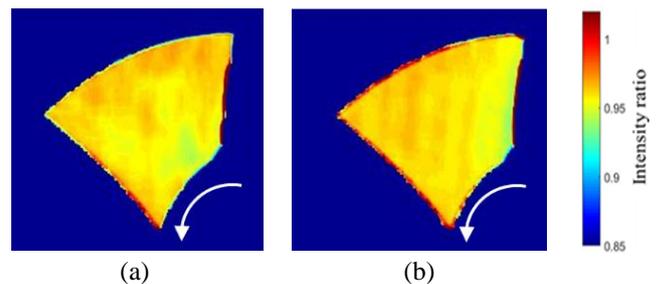


Figure 11 I/I_{ref} intensity ratio contour

The measurement using single-shot lifetime-based method was also performed on the high-speed fan at the same rpm conditions. The temperature and pressure results are shown in Figure 12 and Figure 13. The temperature and pressure are presented in intensity ratio. Due to the limited compression capability and slight aerodynamic heating, the surface temperature and pressure had no obvious gradient on the blade. However, compared to the results of laser-based phase-lock method (as shown in Figure 11), the results had better quality. Comparatively, single-shot lifetime-based method is more suitable for turbocharger applications.



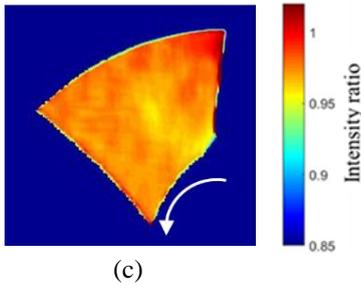


Figure 12 Ratio of ratios fields of TSP (front view) at (a) 5k rpm, (b) 10k rpm, (c) 15k rpm

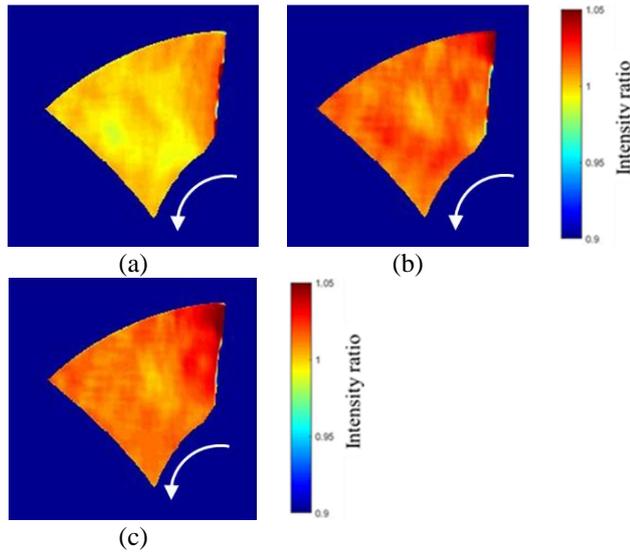


Figure 13 Ratio of ratios fields of PSP (front view) at (a) 5k rpm, (b) 10k rpm, (c) 15k rpm

2. Results of turbocharger compressor experiment

Good quality pressure and temperature results of the compressor blades were obtained using the single-shot lifetime-based method. Figure 14 and Figure 15 shows the temperature and pressure field under three rotation speed conditions: 60k rpm, 90k rpm, 111k rpm. The temperature results are presented in temperature increment ΔT , with reference temperature of 290 K, and the pressure results are presented in pressure ratio normalized by the atmospheric pressure.

For each rotation speed, the minimum temperature was found near the leading edge while the maximum temperature occurred near the trailing edge. As the rotation speed increased, aerodynamic heating became stronger so that the overall temperature on the blade surface increased. As for the pressure fields, generally, the minimum pressure was found at the tip near the leading edge while the maximum pressure occurred near the trailing edge. The streamwise pressure gradient and the overall pressure value became larger when the rotation speed increased due to the higher aerodynamic load on the blade.

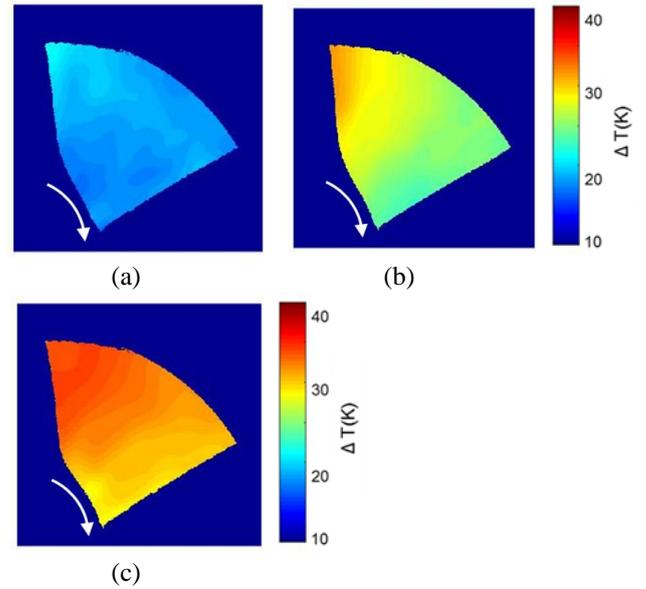


Figure 14 Temperature fields (front view) at (a) 60k rpm, (b) 60k rpm, (c) 111k rpm

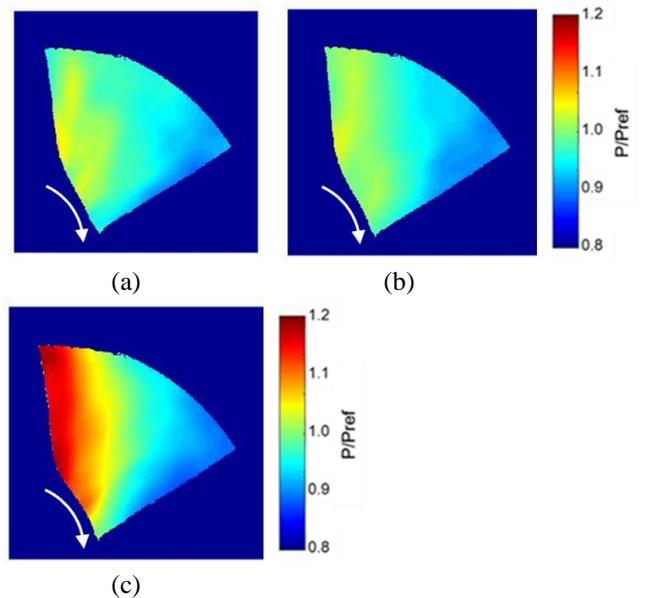


Figure 15 Pressure fields (front view) at (a) 60k rpm, (b) 60k rpm, (c) 111k rpm

CFD simulation was completed by IHI Corporation using the boundary conditions in the experiment. The mesh grid quality and numerical method had been well validated in engineering applications. As shown in Figure 16, the PSP results were compared to CFD data along three meshgrid lines at different radial height.

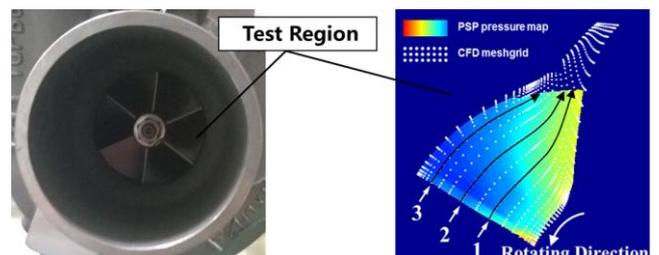


Figure 16 Region of PSP test and CFD mesh grid (front view)

Figure 17 shows the comparison results of 111k rpm. Generally, the axial pressure distribution of both PSP and CFD data showed similar trends. The pressure in the figures are presented in pressure increment ΔP normalized by the pressure P_{ref} at the leading edge of the blade. X/C presents the normalized axial position, where C is the axial chord of the impeller. Along all the three paths, the pressure increased rapidly near the leading edge compared to downstream regions and both PSP and CFD results captured this feature. As for different paths, the PSP and CFD curves shows good agreement near the root region (path1, Figure 17(a)) of the blade, in the middle region (path2, Figure 17(b)) and in the tip region (path3, Figure 17(c)), the PSP pressure value is slight lower than CFD data. A possible reason is the flow field difference in these regions between CFD and PSP experiments.

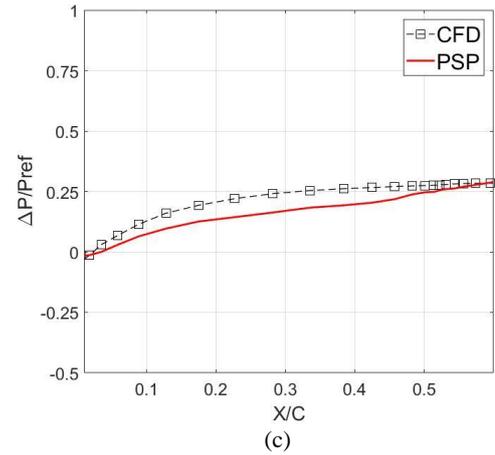


Figure 17 Comparison of PSP and CFD data at 111k rpm along (a) path 1, (b) path 2, (c) path 3

CONCLUSIONS

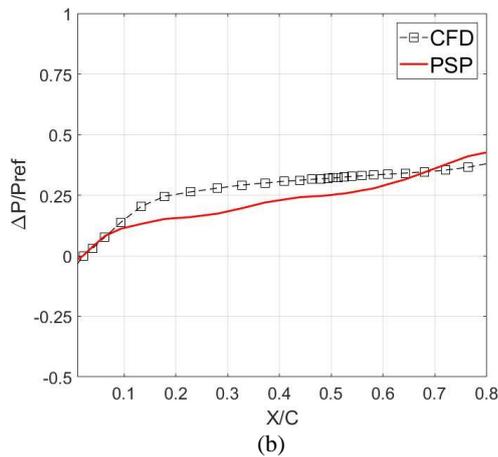
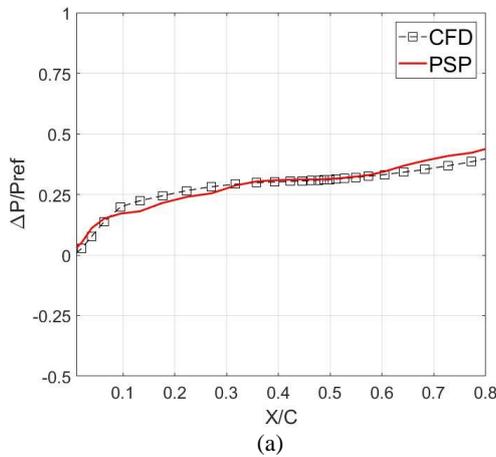
In the current study, two techniques (single-shot lifetime-based method and phase-lock intensity-based method) to apply PSP/TSP to turbomachinery applications were performed. The characteristics of these two methods were compared. As shown in Table 1, the phase-lock intensity-based method could obtain images with good SNR and slight motion blur by increasing number of excitation pulses, however, that reduces the temporal resolution and high quality pulsed light source is necessary. In contrast, the single-shot lifetime-based method is more suitable in turbomachinery applications due to the acceptable SNR and good quality images. Moreover, this method is capable of transient measurement, which is valuable in unsteady flow field diagnosis.

Table 1 Comparison of different PSP/TSP techniques

Methods	Single-shot lifetime-based method	Phase-lock intensity-based method
Characteristics		
SNR	high	high (multi pulses)
Motion blur	serious	slight
Image quality	good	speckles & random patterns
Temporal resolution	transient measurement	time averaging measurement

Temperature and pressure results with a reasonable accuracy were obtained by PSP and TSP using the single-shot lifetime-based method and the results were evaluated by a comparison with CFD. The pressure distribution of PSP and CFD data showed well agreement in most cases. However, some deviation still exists due to the flow field difference between the simulation and the real experiment.

Future work will focus on improved experiments that allow direct comparison between PSP/TSP data and transducer data on static components. It is also important to add transducers at the inlet and outlet of the turbocharger to provide reference information for CFD. In this way, a better match can be achieved between numerical simulations and real experimental conditions.



NOMENCLATURE

A	= Stern-Volmer coefficient
B	= Stern-Volmer coefficient
C	= axial length of the impeller
I_1	= intensity of the first gate
I_2	= intensity of the second gate
I_{ref}	= intensity at reference condition
p	= pressure
p_{ref}	= pressure at reference condition
P_{ref}	= static pressure at the leading edge of the blade
ΔP	= pressure increment
T	= temperature
ΔT	= temperature increment
X	= axial position

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