

## Visualization of Pressure Field over Rotating Blades Using Pressure Sensitive Foil Technique

By Mohammed K. IBRAHIM,<sup>1),2)</sup> Soichiro MATSUMOTO,<sup>2)</sup> Koichi MORI<sup>2)</sup> and Yoshiaki NAKAMURA<sup>2)</sup>

<sup>1)</sup>Aerospace Engineering Department, Faculty of Engineering, University of Cairo, Giza, Egypt

<sup>2)</sup>Aerospace Engineering Department, Graduate School of Engineering, Nagoya University, Nagoya, Japan

(Received May 11th, 2009)

This paper describes a new pressure measurement technique for measuring the pressure over rotating blades of an industrial axial flow fan. The new technique is called the pressure sensitive foil (PS-Foil) technique. In this technique, a very thin aluminum foil is coated with pressure sensitive paint using anodization. The resulting PS-Foil can be stuck on any blade using a very thin layer of silicon. The PS-Foil technique shows a very fast time response like conventional porous anodized aluminum and can be applied to any rotor blade without fabricating the blade from aluminum. The total thickness of the aluminum foil and silicon layer is as small as 200  $\mu\text{m}$ . An intensity based method and prior calibration procedures are used to obtain the calibrated PSP image. The unsteady experimental setup presented here shows that the PS-Foil time response is on the order 30  $\mu\text{s}$  which is close to the conventional porous anodized aluminum method. Two applications are considered here to assess the applicability of this technique. Subsonic jet-plate impingement, and rotating blade of industrial fan. The pressure distribution over the impingement plate at different plate angles, and over the rotating blade at various speeds could be obtained with sufficient spatial resolution.

**Key Words:** Pressure Sensitive Paint, Turbomachines, Subsonic Jet-Plate Impingement

### Nomenclature

$A$ :	Stern-Volmer relation first constant
AA:	anodized aluminum
$B$ :	Stern-Volmer relation second constant
CCD:	charge-coupled device
$D$ :	nozzle exit diameter
$I$ :	luminescent intensity
$I_{\text{ref}}$ :	luminescent intensity at reference condition
ICCD:	intensified charge-coupled device
$M$ :	Mach number
$P$ :	total pressure
$p$ :	pressure
PMT:	photomultiplier tubes
PSP:	pressure sensitive paints
R.P.M:	revolution per minutes
$T$ :	temperature
TSP:	temperature sensitive paint
$x, y, z$ :	Cartesian coordinates
Ru(ph <sub>2</sub> -phen):	bathophen ruthenium chloride
$\lambda$ :	luminescent emission wavelength
$\tau$ :	response time
$\theta$ :	plate inclination angle in degrees
Subscripts	
exit:	nozzle exit condition
max:	maximum value
min:	minimum value
ref:	reference condition
$x, y, z$ :	Cartesian coordinates
$\infty$ :	ambient condition

### 1. Introduction

Blade surface pressure measurement techniques are needed to help understand flow behavior in turbomachines. Early surface pressure measurements of subsonic rotors were made by Sexton, O'Brien and Moses<sup>1)</sup> using blade-mounted pressure transducers and multi-channel radio telemetry. Today, blade-mounted pressure transducers are the only way to measure surface pressure on rotors. Unfortunately, such transducers cover a limited region of the blade due to a compromise in the structural integrity of the blade and flow integrity.

PSP is a promising technique for measuring the surface pressure distributions on high-speed rotating blades in turbomachinery where conventional techniques are difficult to use. Recent PSP measurements on rotating machinery were conducted by Burns and Sullivan<sup>2)</sup> with a laser-PMT system. They obtained the pressure distribution on a small wooden propeller. Mosharv et al.,<sup>3)</sup> obtained the pressure distribution on propellers using a CCD camera system with pulsed light source.

PSP measurements on helicopter rotor blades were carried out at TsAGI (Central Aero-Hydrodynamic Institute) in Russia<sup>4)</sup> and NASA Ames.<sup>5)</sup> Navarra et al.,<sup>6)</sup> obtained pressure images on a rotor blade using an ICCD camera system. Hurbner et al.,<sup>7)</sup> suggested a lifetime imaging method for PSP measurements on a rotating object based on detecting the luminescent decay traces of a rotating painted surface on a CCD camera. Liu et al.,<sup>8)</sup> and Bencic<sup>9)</sup> reported PSP measurement on a rotating blade using both laser scanning and CCD camera, respectively. In these works,

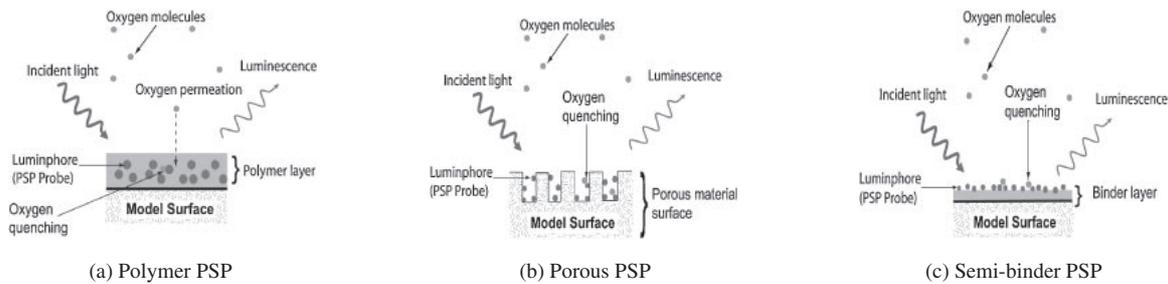


Fig. 1. Schematic of surface luminescent painting methods.

research focused on time-average pressure measurements. Most propellers and front stages of compressors have steady pressure distributions over the blade surface. However, in some applications, the pressure over the blade is unsteady and information on the unsteady variation over the whole blade areas is interesting to designers and is very challenging. Recently, Gregory<sup>10)</sup> carried out unsteady PSP measurements using polymer/ceramic (PC-PSP) in a high-speed turbocharger.

There are two basic PSP techniques: conventional polymer PSP, and porous PSP. Figure 1(a) and Fig. 1(b) shows a schematic comparison. In conventional polymer PSP as shown in Fig. 1(a), oxygen molecules in the working gas permeate the polymer layer binder and quench the luminescence. The main advantage of using polymer as a binder for PSP is its simple application. However, its time response is slow compared to the porous PSP technique.

By contrast, as shown in Fig. 1(b), a porous PSP has a much larger open surface where luminophore molecules are applied directly; oxygen molecules can directly quench the luminescence without permeating into the binder layer. Therefore, use of a porous material as a binder for PSP has two advantages. First, a very fast response time (on the order of microseconds) for unsteady PSP measurements. Second, it enables PSP measurements at cryogenic temperatures where oxygen diffusion is prevented by a conventional homogeneous polymer.<sup>11)</sup> This technique has two main disadvantages. First, it has high temperature and moisture dependency. Second, implementation is not easy.

Kurita et al.,<sup>12)</sup> proposed a method using a non-oxygen permeation binder to support the luminophore as shown in Fig. 1(c) called semi-binder PSP. The technique showed good results at hypersonic and supersonic speeds. However, it also has poor mechanical properties where the luminophore concentration over the model surface decreases with time due to flow-field interaction with the surface-supported luminophore.

Many industrial turbomachines applications have unsteady and low-speed flows. PSP measurement is challenging at unsteady and low-speed flows where the change in air pressure is very small.

Unsteady applications require very fast PSP response times and minimization of temperature effects. High gas diffusive materials are needed as a binder for unsteady PSP, because the PSP response time depends on gas diffusivity in the binder. Until now, three materials have been used

as binders: (1) commercial porous silica thin-layer chromatography (TLC-PSP); (2) porous anodized aluminum (AA-PSP); and (3) polymer with hard ceramic particles (PC-PSP). The TLC-PSP and AA-PSP methods have a short response time on the order of 10  $\mu$ s.<sup>13)</sup>

In low-speed applications, the major sources of error include but are not limited to the temperature effect, image misalignment, and CCD camera noise. These noise sources must be minimized to obtain acceptable quantitative pressure results at low speeds.<sup>11)</sup> These sources of errors suggest pushing PSP instrumentation to the limit and using pressure correction methods for other sources like temperature and image misalignment.

Most PSP applications for turbomachinery use a conventional polymer PSP. In the present study, a porous PSP used by covering the surface with very thin layer of PSP anodized aluminum foil. To our knowledge, Mérienne et al.<sup>14)</sup> used this technique in a transonic wind tunnel but there has been no attempt to apply this technique to subsonic flow or turbomachines. The present method can be applied to any surface material without actually fabrication from aluminum. The PSP aluminum foil technique is applied to both low-speed plate-jet impingement, and the rotating blade of an industrial fan. The pressure distribution over a rotating blade at various rotation speeds is reported in this study.

### 1.1. PSP theory and measurement method

The physical processes involved in the behavior of PSP have been thoroughly described in the literature.<sup>11)</sup> In PSP technique, a probe molecule embedded in a polymer binder is elevated to an excited state by absorbing light of a particular wavelength. The molecule returns to the ground state by releasing the excitation energy. Energy can be dissipated via emission of light or through radiationless deactivation processes, such as oxygen quenching and thermal quenching. For PSP, the excess energy can be absorbed by oxygen molecules through a process in which energy is transformed to oxygen molecules in a collisional manner. This process, known as oxygen quenching, depends upon the concentration of oxygen molecules. Since the concentration of oxygen molecules is proportional to the partial pressure of oxygen, luminescence is sensitive to pressure due to the oxygen quenching process and can be modeled by the Stern-Volmer relation.<sup>11)</sup>

$$\frac{I_{\text{ref}}}{I} = A + B \frac{p}{p_{\text{ref}}} \quad (1)$$

where  $A$  and  $B$  are coefficients determined experimentally,  $I$  is the measured intensity,  $I_{\text{ref}}$  is a reference luminescent intensity,  $p$  is the pressure, and  $p_{\text{ref}}$  is the reference pressure. In general, coefficients  $A$  and  $B$  are temperature dependent. In typical tests in a wind tunnel,  $I_{\text{ref}}$  is taken when the tunnel is turned off so it is often called the wind-off intensity (or image); likewise,  $I$  is called the wind-on intensity (or image).

In this study, the PSP is applied over the blade of an axial flow fan by covering the blade with a very thin porous anodized aluminum (AA) foil coated with pressure sensitive paint. The foil thickness is about  $200\ \mu\text{m}$  and a silicon layer of about  $50\ \mu\text{m}$  is used to stick the PSP aluminum foil to the blade. The pressure-sensitive dye used in this study is bathophen ruthenium chloride. The preparation of AA-PSP is described elsewhere.<sup>13,15,16</sup> The aluminum foil is pure aluminum (1050). PSP intensity based method and prior calibration procedures are considered in this study.

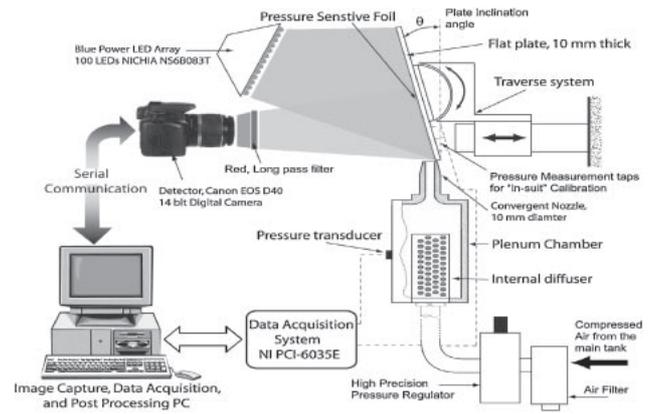
## 2. Experimental Facility

### 2.1. Subsonic jet-plate impingement

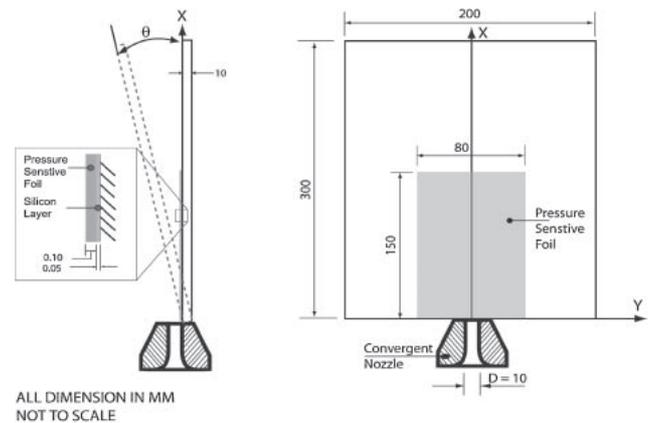
Subsonic jet-plate impingement experiments were conducted at the Open Jet facility in the Department of Aerospace Engineering, Nagoya University. A subsonic jet is exhausted inside an anechoic chamber as shown in Fig. 2(a). The nozzle in this study was convergent nozzle with an exit diameter of 10 mm and was attached to a cylindrical plenum chamber with a diameter of 220 mm and a length of 400 mm. The plate, which causes interaction with the jet, is made of aluminum alloy containing Mg, Fe, Cr and Si (Japanese Industrial Standards (JIS) A5052) and has a length of 300 mm, a width of 200 mm, and a thickness of 10 mm. Figure 2(a) shows a schematic of the experimental setup. The plate is supported over traverse system with four degrees of freedom.

The plate moves in the  $x$ ,  $y$ , and  $z$  directions with respect to the center of nozzle exit. The plate inclination angle ( $\theta$ ) can be varied from  $0^\circ$  to  $30^\circ$ . The coordinate system is shown in Fig. 2(b).

High-pressure air is supplied from a  $12\ \text{m}^3$  tank at a pressure of  $12\ \text{kgf}/\text{cm}^2$ . This tank is connected to the plenum chamber via a high-pressure pipe with an inner diameter of 1 inch. A high-precision pressure regulator and solenoid valve were used to control the pressure inside the plenum chamber to within an accuracy of 0.25%. The solenoid valve is opened and closed via a signal from the data acquisition PC (DAQ-PC) with a data acquisition board (National Instruments, PCI-6035E) The DAQ-PC is connected to a 6-channel DC strain amplifier (KYOWA DPM-6H) with a frequency response of 5 kHz, which is in turn connected to various pressure transducers and load cells. The pressure transducers monitor the pressure inside the plenum chamber as well as measuring the pressure on the plate surface. Twenty pressure taps were used to measure the pressure on the plate centerline, where the jet impinges on the plate, using a single pressure transducer and scanivalve for in-situ PSP calibration and/or comparison with PSP results.



(a) Experimental setup for jet-plate impingement



(b) Coordinate system

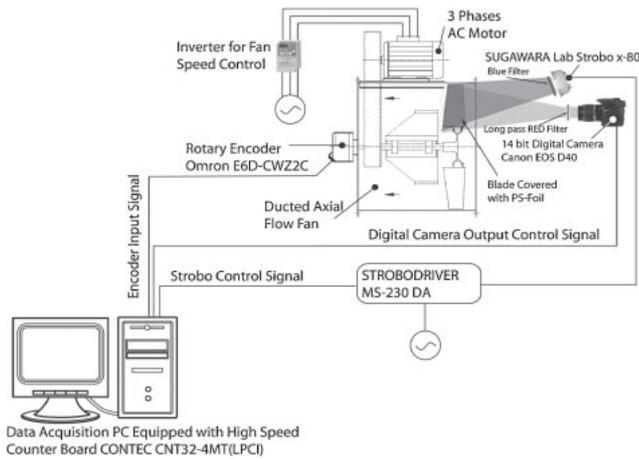
Fig. 2. Schematic, photo, and coordinate system of jet-plate impingement setup.

At data acquisition, transducer zero errors were monitored before each run, and the plenum chamber and ambient pressures were also checked for each run to normalize measured data.

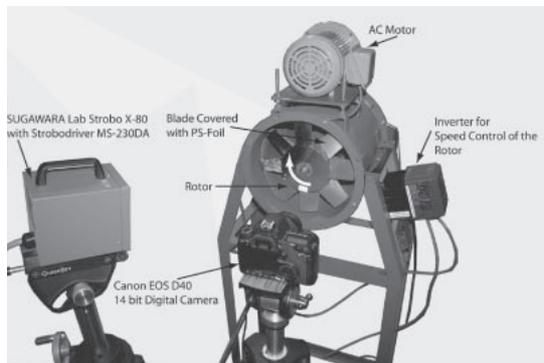
### 2.2. Rotating blade of industrial axial flow fan

Figure 3 shows the experimental facility for the rotating blade of industrial axial flow fan PSP experiments. The axial flow fan in this study was a FURUTA AF-300 SP(B). The specifications are listed in Table 1 and shown in Fig. 4(a). Figure 4(b) shows the profile of the fan blade at three different stations along the radial direction. The blade is characterized by low twist which eases application of the PS-Foil.

To obtain high-quality PSP images, wind-on and wind-off images must have exactly the same position. To achieve this requirement, an incremental encoder OMRON E6D with 3600 pulses per revolution was mounted along the fan axis. A PC with high-speed counter board (CONTEC CNT32-4MT(LPCI)) was connected to the encoder. The counter board outputs were connected to the strobe and CCD Camera (Canon EOS D40). A trigger signal from the board fires the strobe when the PSP blade reaches a preset angular location, which is exactly the same as the wind-off image. The total delay in the counter board is about 200 ns which having a negligible effect on image alignment.



(a) Experimental setup of PSP rotating blade



(b) Photo of experimental setup of PSP rotating blade

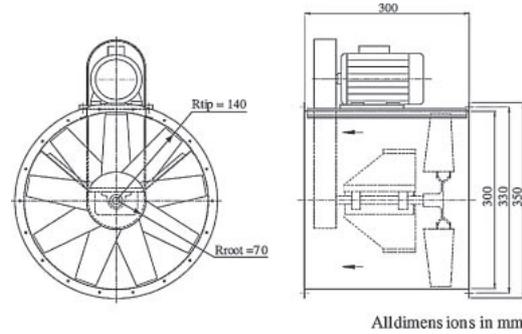
Fig. 3. Schematic and photo of PSP rotating blade setup.

Table 1. FURUTA AF-300 SP(B) axial flow fan specifications.

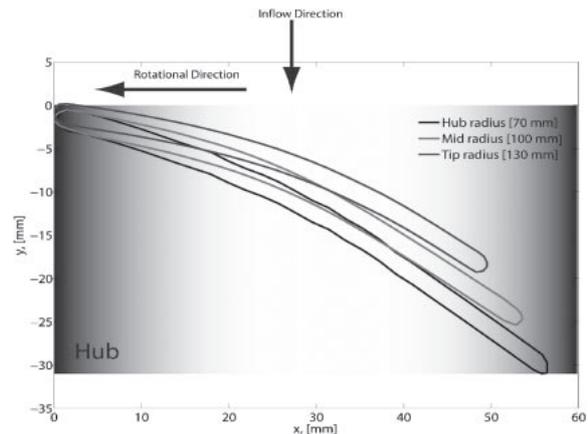
Motor power	0.4 kW
Designed maximum rotational speed	3250 rpm
Maximum flow rate	42 m <sup>3</sup> /min at 3250 rpm
Static pressure	25 mmAq
Number of rotor blades	8
Rotor diameter	300 mm
Blade taper ratio	0.82
Tip radius/hub radius	2
Thickness/chord at mean radius	0.044

**2.3. Unsteady characteristics**

To explore the time response of the proposed PS-Foil, a simple shock-tube experiment was conducted. Figure 5 shows the schematic. The total length of the driven section of the shock tube was 2 m. The test specimen was placed at one side inside the driven section of the tube 1.4 m from the diaphragm. A window was installed opposite the test specimen for optical observation. The excitation light source was 8 blue LEDs (NICHIA NSPB510S, wavelength: 450–480 nm). The detector was a photomultiplier tube (Hamamatsu R374). A long-pass filter passing luminescence with a wave-length ( $\lambda$ ) longer than 580 nm at 80% intensity was installed in front of the photomultiplier tube. A flush-



(a) FURUTA AF-300 SP(B) axial flow fan configuration and dimensions



(b) Blade profile

Fig. 4. Axial flow fan layout and blade profile.

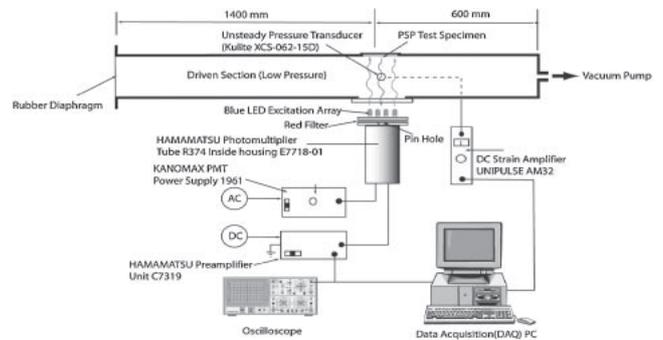


Fig. 5. Shock tube experimental setup.

mount high-speed pressure transducer (Kulite XCS-062-15D) was installed at the same location of specimen. This transducer is connected to a single-channel dynamic DC strain amplifier (SAN-EI 6M71) with a frequency response of 100 kHz. Both the photomultiplier tube and pressure transducer output signals were recorded using DAQ-PC and measurements were acquired at a sampling rate of 100 kHz.

**2.4. PSP hardware and software**

For subsonic-jet impingement experiments, the photo-detector in this study was a CCD 14-bit Canon EOS camera D40 with a resolution of 2592 × 3888 pixels. The excitation light source was an array of 100 power blue LEDs (NICHIA

NSB083T, wavelength: 450 nm). The image capture rate was one frame per 0.25 s. Experiments showed that the capture rate is very dependent on the excitation light and shutter opening. The camera was completely controlled through the PC via a serial port using the Canon Remote Capture software. In all experiments, the luminescence that the CCD camera detected was filtered to prevent unnecessary illuminating luminescence. The filter was a long-pass filter passing luminescence with a wave length ( $\lambda$ ) longer than 580 nm at 80% intensity.

To obtain calibrated PSP images, an intensity based method was used in this study. The basic processing procedure calculates the ratio between the wind-on image and wind-off reference image to correct the effects of non-homogeneous illumination, uneven paint thicknesses and non-uniform luminophore concentrations. However, this proportioning procedure is complicated by model deformation caused by aerodynamic loads, which results in misalignment between wind-on and wind-off images. By increasing the plate thickness and stiffening the support system this deformation can be reduced but it cannot be completely removed and generates noise in the resulting image. Therefore additional correction procedures are required to eliminate error sources associated with model deformation. These correction procedures are not implemented in this study and neither are the temperature effects of PSP and self-illumination noise. However, to reduce the temperature change between wind-off and wind-on images, wind-off images were taken immediately after wind-on images not before. Noise caused by darkness is reduced by subtracting the dark image from the data image. A code was developed for post-processing and calibration. Simultaneous pressure measurements and image capture processing are included in this post-processing code for online processing of PSP images.

The same system was used for rotating-blade experiments except for the excitation light. The PSP was illuminated using a blue filter centered at 450 nm along with a SUGAWARA strobe with xenon flash lamp X-80 with a 2  $\mu$ s flash duration driven by a SUGAWARA strobedriver MS-230DA. Note that a 2- $\mu$ s flash duration roughly corresponds to 0.125-mm blurring on blades at 4000 rpm. Images were acquired and integrated over 375 revolutions using excitation by multiple flashes while the camera shutter was held open until an acceptable CCD well capacity was achieved. Wind-off images were taken immediately after wind-on images.

### 3. Results

Figure 6 shows the pressure distribution along the plate centerline at  $y = 0$  for both pressure taps data and pressure data extracted from calibrated PSP images at different plate inclination angles. At low inclination angles ( $\theta$ ) of  $0^\circ$  and  $5^\circ$ , there is acceptable agreement between both pressure taps data and PSP data. As the inclination angle increases to  $10^\circ$ ,  $15^\circ$  and  $20^\circ$ , there is large deviation near the nozzle exit

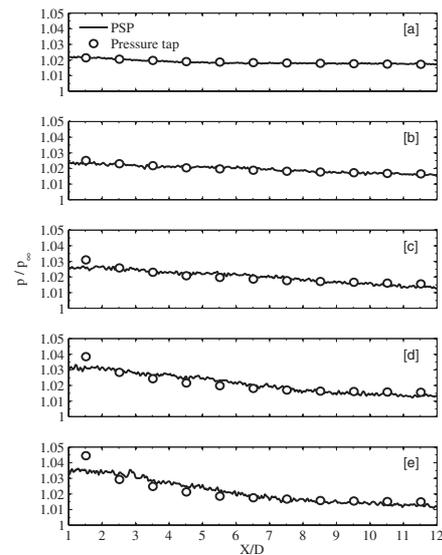


Fig. 6. Comparison of PSP and pressure tap data at plate centerline for  $M_{\text{exit}} = 0.6$ : a)  $\theta = 0^\circ$ , b)  $\theta = 5^\circ$ , c)  $\theta = 10^\circ$ , d)  $\theta = 15^\circ$  and e)  $\theta = 20^\circ$ .

and good agreement downstream. The deviation occurs in high-pressure regions. This is attributed to the temperature effect on PSP data and it highlights the importance of correcting the present PSP data to include the temperature effect using temperature sensitive paint (TSP) data. Figure 7 shows pressure images mapped onto the plate surface for different plate inclination angles. The jet signature on the whole plate is clearly captured using the proposed PS-Foil technique.

The unsteady characteristics of the proposed PS-Foil technique were explored using the simple shock tube experiments described in section 2.3. Figure 8(a) shows a typical pressure signal from the PS-Foil, semi-binder PSP, and pressure transducer, along with the theoretical pressure jumps associated with the incident and reflected normal shock waves. The PS-Foil followed the sharp pressure rises after the incident and reflected shock waves passed through the PSP test specimen excited by the blue LEDs. Figure 8(b) shows the normalized pressure signal from the PS-Foil, semi-binder PSP, and pressure transducer. The normalized pressure response to step input is well represented by a first-order model described by the following equation:

$$\frac{p - p_{\min}}{p_{\max} - p_{\min}} = 1 - e^{-\frac{x}{\tau}} \quad (2)$$

where  $\tau$  is the response time.  $\tau$  was found to be 20, 30, and 500  $\mu$ s for pressure transducer, PS-Foil, and semi-binder PSP, respectively. The present value for the response time of the PS-Foil is the same as that for AA-PSP with a thickness of 4.3  $\mu$ m measured by Sakaue.<sup>17)</sup>

Figures 9 shows the pressure distribution over the suction side of the rotating blade at three different rotational speeds: 3000, 4000, and 5000 rpm. Clearly the maximum pressure value is lower than the ambient pressure. A high-pressure region is observed near the blade leading edge compared to the trailing edge as shown in Fig. 9(a) for a rotational

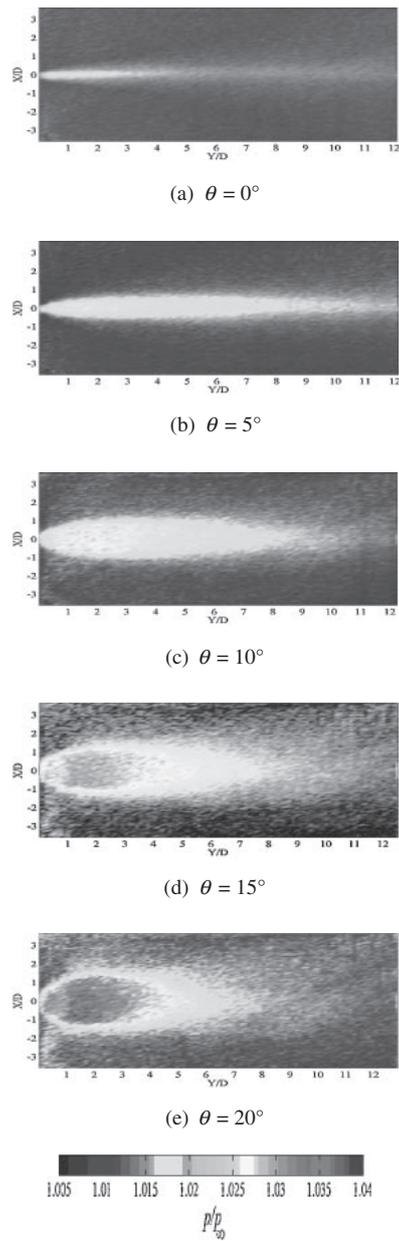
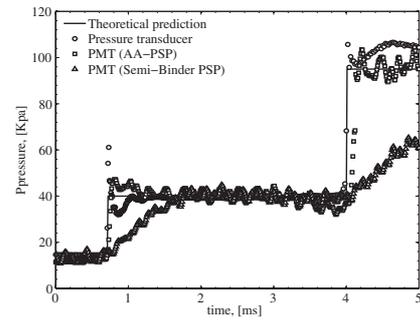
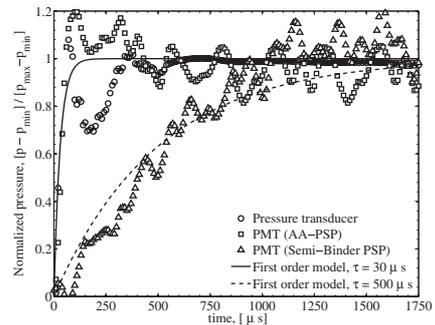


Fig. 7. Pressure images mapped onto plate surface at different plate inclination angles for  $M_{exit} = 0.6$ .

speed of 3000rpm, which is near the design point of the present fan (Table 1). At this rotational speed the flow rate is about  $40\text{ m}^3/\text{minute}$ . Assuming a uniform inlet flow, this corresponds to an axial velocity of about 15 m/s. At the tip radius, the rotational speed is about 44 m/s. These two velocities have a resultant velocity of 46.5 m/s with an inlet flow angle of  $19^\circ$  with respect to the tangential direction. The blade angle at the tip and hub radius is about  $7^\circ$  and  $15^\circ$ , respectively, meaning that the angle of attack at the tip radius is negative leading to an increase in the surface pressure of the suction side at the leading edge compared to the trailing edge.



(a) Pressure history



(b) Normalized pressure response

Fig. 8. Pressure history and normalized pressure response of PS-Foil, semi-binder PSP, and pressure transducer compared to theoretical calculation of simple shock tube experiment.

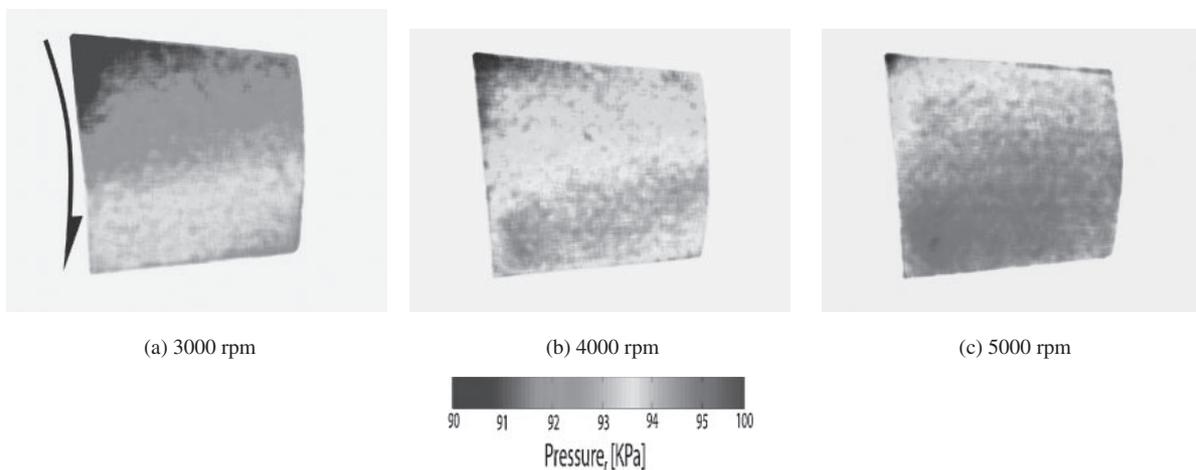


Fig. 9. Pressure distributions over suction side of rotating blade at different rotational speeds.

There is clear variation in the pressure distribution in the radial direction for this rotational speed. This is attributed to the decreasing fan radius, which in turn decreases the resultant velocity and increases the flow angle, assuming that the axial velocity is constant. The pressure decreases near the trailing edge at this rotational speed. A similar pressure distribution pattern is observed at a rotational speed of 4000 rpm as shown in Fig. 9(b). At higher rotational speeds, the fan operates at off-design conditions and its efficiency decreases. Figure 9(c), shows that the pressure increases over the whole blade surface with increasing rotational speed. Validation of the current experimental data is in progress using numerical simulation.

#### 4. Conclusion

A new implementation of the AA-PSP technique is presented here. In this technique, a very thin aluminum foil is coated with pressure sensitive paint using anodization. The resulting pressure sensitive foil (PS-Foil) can be stuck over any surface using very thin silicon. Both unsteady characteristics of the PS-foil and steady low-speed performance were investigated. Two steady low-speed test cases were considered. The first acquire a PSP images over a flat plate due to impingement of a subsonic jet at Mach number 0.6 for different flat plate inclination angles. The second acquire a PSP images over the suction side of a rotating blade of an industrial axial flow fan at different rotational speeds. Results showed that the PS-Foil technique has very fast response times ( $\tau = 30 \mu\text{s}$ ) and high spatial resolution compared to conventional PSP-binder techniques. The PS-Foil can detect pressures as low as 1 kPa. However, at high-pressure regions, a discrepancy between PSP data and pressure tap data is observed. This discrepancy might be attributed to a temperature effect, which was excluded in the present study. With suitable temperature correction, the present technique, will be useful to analyze the unsteady flow field in turbomachines due to stator-rotor interactions or due to surge-related unsteady flow fields in axial flow compressors.

#### Acknowledgments

The authors gratefully acknowledge the financial support provided by Nagoya University 21st Century Micro and Nano Mechatronics COE and 21st Century COE "Frontiers of Computational Science". The first author would also like to thank Mr. Kazuyuki Nakakita of the Japan Aerospace Exploration Agency (JAXA) and Professor Keisuke Asai in the Department of Aerospace Engineering, Tohoku University, for valuable advice.

#### References

- 1) Sexton, M. R., O'Brien, W. F. and Moses, H. L.: An on Rotor Investigation of Rotating Stall in an Axial Compressor, Defense Technical Information Center (DTIC) Technical Report, Cameron Station, Alexandria, VA, 1973, pp. 33.1–33.10.
- 2) Burns, S. and Sullivan, J.: The Use of Pressure Sensitive Paints on Rotating Machinery, Proceedings of 16th Int'l Congress of Instrumentation in Aerospace Simulations Facilities (ICIASF), Institute of Electrical and Electronic Engineers, Wright-Patterson Air Force Base, Dayton, OH, USA, 1995, pp. 32.1–32.14.
- 3) Mesharov, V. E., Radchenko, V. N. and Fonov, S. D.: Luminescent Pressure Sensors in Aerodynamic Experiments, Central Aero-Hydrodynamic Institute (TsAGI), cWA International Corporation, Moscow, 1997.
- 4) Bukov, A., Fonov, S., Mosharov, V., Orlov, A., Pesetsky, V. and Radchenko, V.: Study Result for the Application of Two-Component PSP Technology to Aerodynamic Experiment, AGARD Conference Proceedings CP-601, Advanced Aerodynamic Measurement Technology, 1997, pp. 29.1–29.8.
- 5) Schairer, E. T., Hand, L., Bell, J. H. and Mehta, R.: Application of Pressure Sensitive Paint to Helicopter Rotor, Proceedings of Sixth Annual Pressure Sensitive Paint Workshop, The Boeing Company, Seattle, Washington, October 6–8, 1998, pp. 4.1–4.15.
- 6) Navarra, K., Goss, L., Jordan, J., Rabe, D., Gord, J. and Car, D.: Optical Measurements of Surface Pressure and Temperature in Turbomachinery, AGARD-CP-598, Advanced Non-Intrusive Instrumentation for Propulsion Engines, 1998, pp. 18.1–18.13.
- 7) Hubner, J. P., Abbitt, J. D. and Carroll, B. F.: Pressure Measurement on Rotating Machinery Using Lifetime Imaging of Pressure Sensitive Paint, AIAA Paper 96-2934, 1996.
- 8) Liu, T., Johnston, R., Torgerson, S., Fleeter, S. and Sullivan, J. P.: Rotor Blade Pressure Measurement in a High Speed Axial Compressor Using Pressure and Temperature Sensitive Paints, AIAA Paper 97-0162, 1997.
- 9) Bencic, T. J.: Pressure Sensitive Paint Measurements on a Scale-Model Fans using Luminescent Paints, AIAA Paper 98-3452, 1998.
- 10) Gregory, J. W.: Porous Pressure-Sensitive Paints for Measurements of Unsteady Pressure in Turbomachinery, AIAA Paper 2004-0294, 2004.
- 11) Liu, T. and Sullivan, J. P.: *Pressure and Temperature Sensitive Paints*, Springer-Verlag, Berlin Heidelberg, 2005.
- 12) Kurita, M., Okada, T., Sakuma, R. and Nakamura, Y.: Pressure and Temperature Sensitive Paint Measurement in Shock Tunnel, *J. Visualization Soc. Jpn.*, **22** (2002), pp. 329–332.
- 13) Kameda, M., Tabei, T., Nakakita, K., Sakaue, H. and Asai, K.: Image Measurements of Unsteady Pressure Fluctuation by a Pressure-Sensitive Coating on Porous Anodized Aluminium, *Meas. Sci. Technol.*, **16** (2005), pp. 2517–2524.
- 14) Mérienne, M.-C., Sant, Y. L. and Ancelle, J.: Unsteady Pressure Measurement Instrumentation using Anodized-Aluminium PSP Applied in A Transonic Wind Tunnel, *Meas. Sci. Technol.*, **15** (2004), pp. 2349–2360.
- 15) Sakaue, H., Tabei, T. and Kameda, M.: Hydrophobic Monolayer Coating on Anodized Aluminum Pressure Sensitive Paint, *Sensors and Actuators B*, **119** (2006), pp. 504–511.
- 16) Sakaue, H.: Luminophore Application Method of Anodized Aluminium Pressure Sensitive Paint as a Fast Responding Global Pressure Sensor, *Rev. Sci. Instrum.*, **76** (2005), p. 16.
- 17) Sakaue, H.: Porous Pressure Sensitive Paints for Aerodynamic Applications, Master Thesis, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, 1999.