Unsteady Pressure Measurement of Fan Stator Vane Using Pressure Sensitive Paint

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Abstract

The pressure sensitive paint (PSP) technique has been well established in external flow field. However, there are still unresolved issues in internal flow field. This work was focused on the application to unsteady pressure measurement of fan flow field. The PSP measurement system was established and the image processing software was developed. First, the performance of PSP was investigated at the static cell. Then the unsteady PSP measurement was carried out at fan test facility. PSP data images were acquired from the suction and pressure surface of stator vanes. Pressure distributions on the surface of the stator vane were detected non-intrusively. The issues of image acquisition and image processing were clarified through the practical PSP application to fan flow field.

Introduction

Next generation commercial aircraft will require a low noise aero-engine. Fan noise is the major component of noises radiated from aero-engine. The main cause of fan noise is the interaction between wake induced by rotor and stator shown in Figure1. CFD and theoretical approach are useful tools in order to understand the fan flow field and predict the noise. The former researchers using CFD and theoretical approach clarified that one of the noise sources seem to be the pressure fluctuation on the stator vane. However, the validation of these numerical results has not been enough conducted yet. One of the reasons is that it is difficult to measure the pressure fluctuation directly using conventional sensor such as semi-conductor pressure sensor. When a conventional sensor is used, there is not enough space inside the vane and pressure taps are limited to providing data at discrete points. Not only is spatial limitation an issue, but also the aerodynamic and structural dynamic of the model can be seriously altered by modifications to accommodate the sensors.

So, we have focused on Pressure Sensitive Paint (PSP) technique. The PSP technique has been mainly applied for transonic and supersonic flow since the 1990's by many researchers all over the world. The PSP is a molecular sensor, which uses thin layer of functional chemicals that are sensitive to pressure. A coating of PSP can be applied to any test article and then photo-exited by a laser or other illumination. Pressure on the surface can be measured by detecting luminescence from molecules using PMT or CCD camera. The PSP is a non-intrusive optical measurement technique and is very attractive measurement method. Most of PSP have developed in order to capture the steady pressure distributions on the test model at the wind tunnel. Recently the new PSP coating procedure for faster response was developed. Unsteady measurement applications have been conducted at high speed and external flow conditions. Now the PSP technique is well established in external aerodynamics. However more practical applications such as internal aerodynamics and turbo machinery are rather limited. There are still many unresolved problems complicating the PSP use, accuracy and reliability at low speed condition and internal flow field. For example, in the low speed case high-pressure condition more than ambient pressure (100kPa) decreases sensitivity and dynamic range due to small pressure changes.

We applied the PSP technique to the fan test facility. Our goal is to capture pressure fluctuation on the fan stator vane induced by interaction between rotor wake and stator. So that it will be possible to clarify fan noise source and to evaluate the numerical results. This paper begins with setting up our PSP measurement system for unsteady and internal flow application. Then the PSP performance is clarified by basic static cell test. Finally, the latest results of practical test at the fan test facility are described. These are discussed, and future work planned is referred.

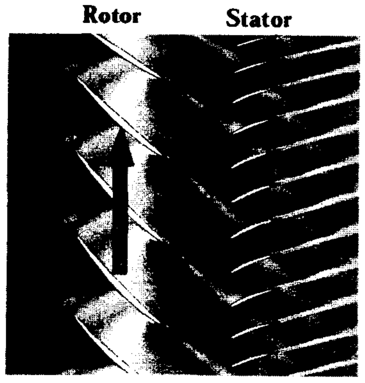

Figure 1 Interaction between Rotor Wake and Stator1)

PSP Theory

Pressure Sensitive Paint is based on the phenomenon of oxygen quenching. For PSP, the excess energy can be absorbed by oxygen molecules through a process in which energy is transferred to oxygen molecules in a collision manner. This process, that is oxygen quenching, depends on 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. The luminescent can be modeled with the following Stern-Volmer relation.

$$\frac{I_{ref}}{I} = A + B \cdot \frac{P}{P_{ref}}$$

Here A and B are the coefficients to be determined experimentally. I is the luminescent intensity and P is the pressure. The index ref is reference condition. In practical measurement, a reference image for a CCD camera system is taken before the experiment. This is wind-off image. The intensity I is measured under the test condition. The I_{ref}/I ratio can remove non-uniformities in illumination and luminescent intensity variations due to uneven surface conditions, that is non-uniformity of paint thickness. The luminescence intensity is inversely proportional to the pressure. Figure 2 shows PSP concept.

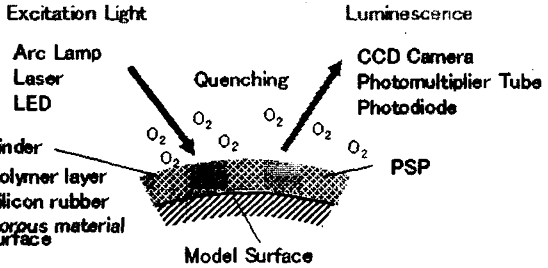

Figure 2 PSP Measurement Concept

PSP Performance

PSP selection

In the present work, Ar-ion laser system was used as the excitation light. The wavelength of its beam is from 457.9nm to 514.5nm. The suitable PSP for the wavelength of the Ar-ion laser is $Ru(dpp)_3Cl_2$, Bathophen ruthenium chloride. Figure 3 shows the excitation and emission spectra of $Ru(dpp)_3Cl_2$. When $Ru(dpp)_3Cl_2$ is excited by the light which wavelength is around 460nm, the luminescence around 620nm is emitted.

Binder

Binder is necessary to adsorb PSP on the test model surface. Fast response is also required to capture the pressure fluctuation on the stator vane. The fast response PSP was developed at JAXA[2]. It is consisted of porous anodized aluminum base and pressure sensitive luminophore directly bonding on the aluminum surface. The luminophore in anodized aluminum base PSP is opened to the test gas so that the oxygen molecules are free to interact with the luminophore. Anodized aluminum base PSP has fast time response, more than 10kHz. This fast response PSP has enough fast to apply to measurements for unsteady aerodynamic phenomena.

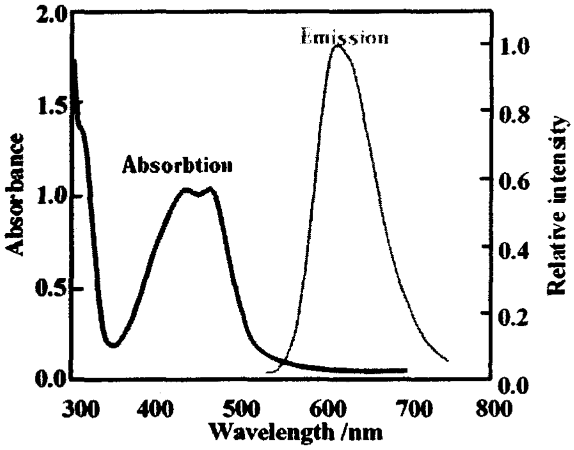

Figure 3 $Ru(dpp)_3Cl_2$ Absorbtion and Emission Spectra[3]

Static Cell Test

A schematic of the static cell system is shown in Figure 4. This system was used to get the static characteristic curve (P/P_{ref} vs I_{ref}/I) of PSP. This test cell was also used as a calibration chamber for the following mentioned test data of the fan test facility. The test piece attached PSP was installed in the static cell. The pressure condition of the static cell was regulated by a vacuum pump and a compressor. The test was carried out for the range of pressure from 20kPa to 400kPa. The temperature of the static cell was constant, approximately 290K. Figure 5 shows the pressure sensitivity of $Ru(dpp)_3Cl_2$. The reference pressure is ambient pressure (100kPa). When P/P_{ref} is more than 1, the pressure sensitivity gets worse and the characteristic curve is described in the nonlinear effect depend on the optical and chemical characteristic of $Ru(dpp)_3Cl_2$. In this case, the relation between the luminescent and pressure was used as polynomial function. This relation doesn't depend on the condition of taking image: lens focus, exposure time, and so on. Furthermore, the luminescent gets dark at high-pressure condition. This shows the difficulty of measurement under the high-pressure conditions.

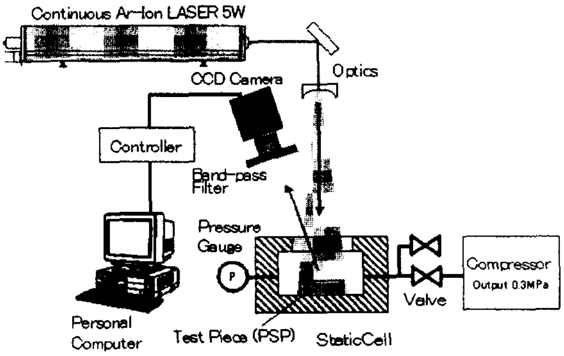

Figure 4 Static Cell System

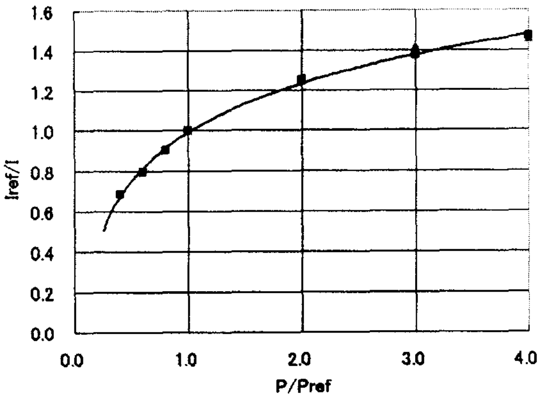

Figure 5 PSP Static Characteristics

Application to Fan Test Facility

Test Setup

Figure 6 shows a photograph of the test setup. This facility has been tested several times for research and development of low noise fan. The specification of this facility is indicated in table 1. The diameter of test section is approximately 0.3m. The luminescent on the stator is observed through the observation window made of acrylic resin (0.05×0.05m). The stators absorbed PSP were installed on the observation window shown in Figure 7. The excitation light source is the continuous Ar-ion Laser system. The luminescence from PSP was detected by the CCD camera, which has 1280×1024-pixel resolution with 12bit depth. A 650nm±20nm band-pass filter was set in front of the CCD camera in order to separate the luminescence from the excitation light. To detect the unsteady pressure changes the exposure time is required to be short as possible. So, the image intensifier device with high-speed shutter was attached on the CCD camera. The short time exposure over 20 μ sec can be conducted. Due to optical limitations, the CCD camera records a skewed two-dimensional image. An example of acquisition image is shown in Figure 9.

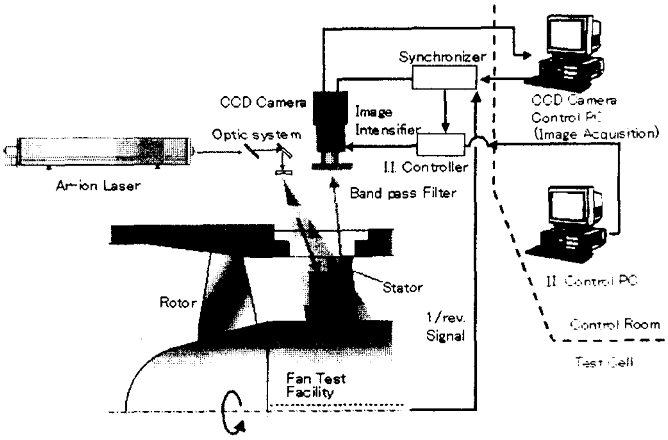

Figure 6 Schematic of Test Setup

Table 1 Major Parameters of Geometry and Design Point Condition

Number of Rotor Blade	18
Number of Stator Vane	45
Hub to Tip Ratio	0.55
Axial Flow Mach Number	0.51
Rotor Tip Mach Number	1.13
Stato Chord / Tip Radius	0.1925
Operating Condition	Design Point
R.P.M. of Design Point	24645

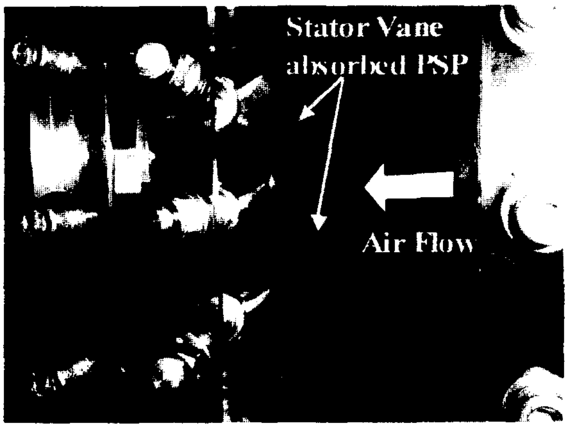

Figure 7 Photo of Stator Vane adsorbed PSP

Data-Acquisition Procedure

For each measurement condition a wind-off reference image and a wind-on test image were recorded. In order to define the thermal noise of CCD and ambient light contamination, the dark image was taken without laser illumination. Once operator sends the command to initiate image acquisition, the CCD camera is charged, and the once-per-revolution pulse (1/rev) from the test article is used to initiate the timing sequence. The 1/rev signal triggers the exposure timing of the image intensifier. The period for capturing a series of images corresponds to the rotor blade passing frequency. The synchronizer plays a role of controlling the time sequence. The unsteady measurement is possible by shifting the trigger timing from the synchronizer.

Image Processing

Noise reduction of acquired image is important for PSP measurement. Camera noise is mainly due to photon shot noise. In the low speed flow condition such as fan flow field, high-pressure condition more than ambient pressure (100kPa) is major. Small pressure change in the low speed condition decreases sensitivity and dynamic range. In addition, the camera noise is also amplified by the image intensifier. Thus the noise reduction must be considered for the present work. Averaging a large number of images and subtracting dark image from wind-off/on images enable a noise reduction. In this work twenty images were averaged in each test condition. Since final image remained noisy, a spatial filtering for each pixel was conducted. After the noise reduction process, the image intensity ratio I_{ref}/I was calculated by dividing the wind-off image by the wind-on image on a pixel-by-pixel basis. The image intensity ratio is assumed to be the model surface pressure via modified Stern-Volmer relation above mentioned. The flowchart of the data reduction is shown in Figure 9.

Results

Time Averaged Pressure Data

Time averaged pressure distributions of stator vanes were obtained using modified Stern-Volmer relation. Figure 10 shows a series of surface pressure maps at different rotational speeds (100%, 80%, and 62%). The pressure on the pressure surface increases gradually from hub to tip. Decreasing the rotational speed makes the level of surface pressure lower. Since the pressure transducer wasn't installed around stator vanes, PSP results couldn't be evaluated quantitatively. So, the result of CFD was applied as a validation data to evaluate the fan flow field. The result of CFD at the 100% speed condition is shown in Figure 11. The result of PSP indicated qualitatively good agreement with the result of CFD.

Unsteady Pressure Data

The pressure histories were extracted at the pixels of the pressure and suction surface, respectively. Figure 12 shows the extracted pixels and pressure histories. As increasing the rotating speed, the level of the pressure becomes higher and the fluctuation becomes larger. The pressure and fluctuation of the pressure surface are larger than the suction surface. The results of the FFT analysis of the pressure data are shown in Figure 13. The peak frequencies at the pressure surface and suction surface of the stator vane s correspond to the rotor blade passing frequencies. The power level becomes higher as increasing rotor speeds. These results indicate that the PSP technique can detect the phenomena of the fan flow field. Currently, the data analysis is underway in detail. In the future work, the improvement of the acquisition and image processing procedures will be conducted for the more sufficient noise reduction efficiently.

Conclusions

In this work, valuable experience was gotten from the application of the non-intrusive PSP technique to measurement in the fan flow field. The development of the PSP measurement system and procedure, test setup, data acquisition, and image processing was presented. The PSP data acquired from the fan stator vane were indicated. The results show that the PSP technique can be successfully used in the unsteady flow condition and the potential of the PSP technique.

On the other hand, the issues were encountered in this work. Those are the procedures of the noise reduction of images recorded and the image processing. If these issues are solved, the accuracy is improved. The data acquired by improved PSP technique will be used to evaluate the results of numerical works. These efforts will contribute to clarify the mechanism of the fan noise radiation process in the future.

References

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3) MOSAIC Project web site: http://www.nal.go.jp/fluid/eng/mosaic/index.html

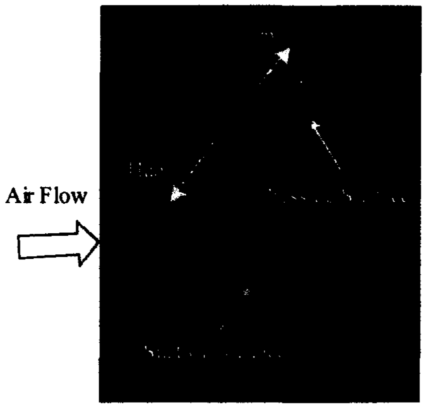


Figure 8 Sample of Acquisition Image

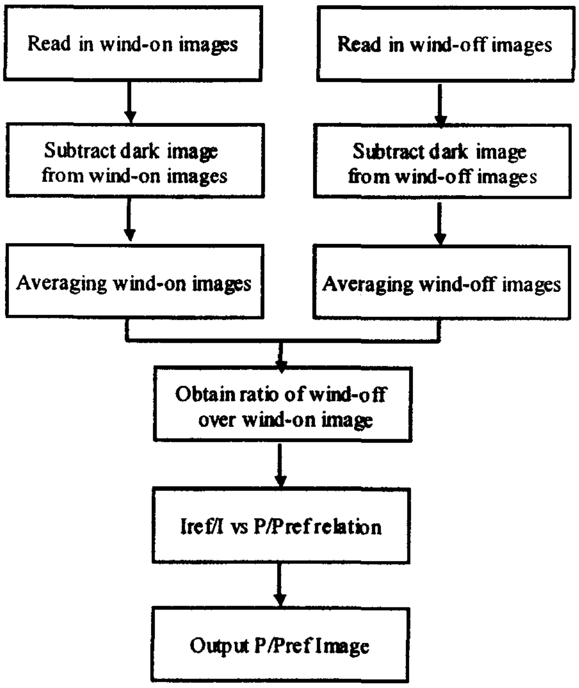
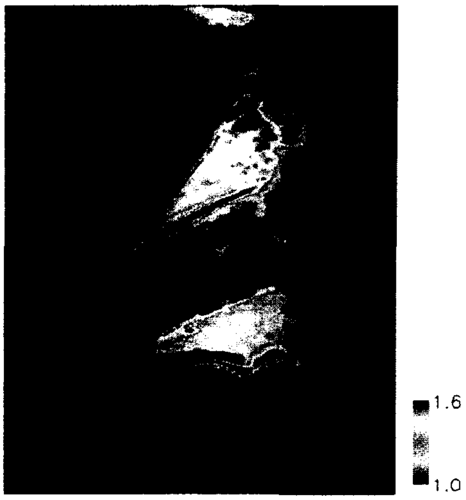
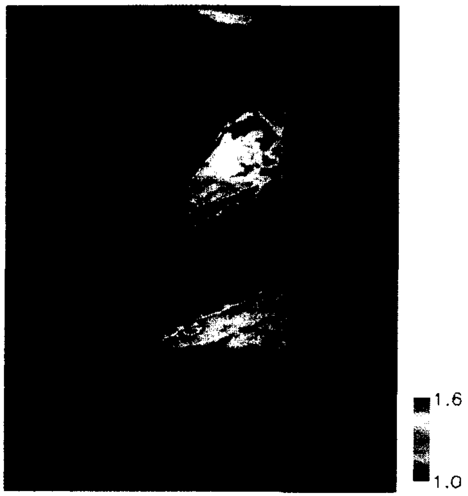


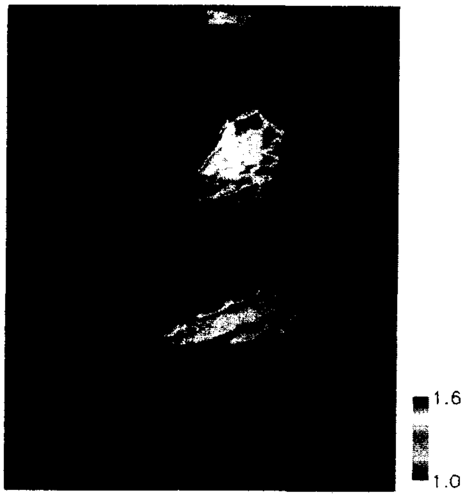
Figure 9 Image Processing Flow chart



(a) 100% speed (Design Point)



(b) 80% speed



(c) 62% speed

Figure 10 Time-averaged pressure P/P_{ref} Map

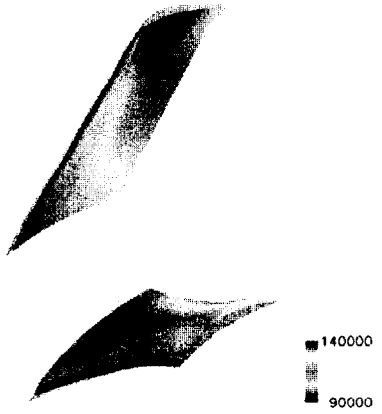
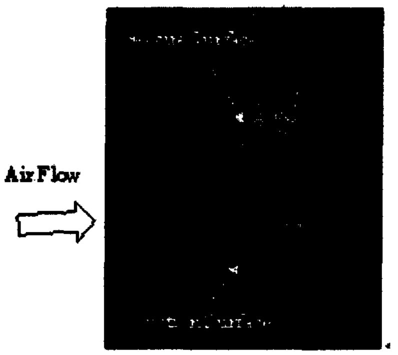
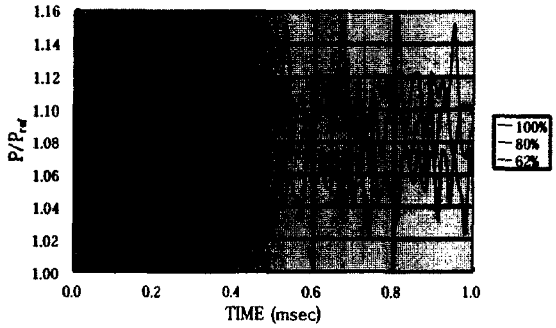


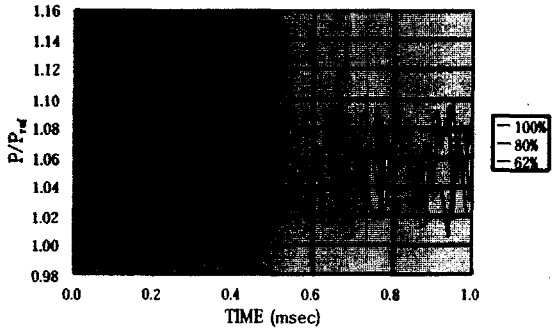
Figure 11 Result of CFD at 100% speed



(a) Extracted points

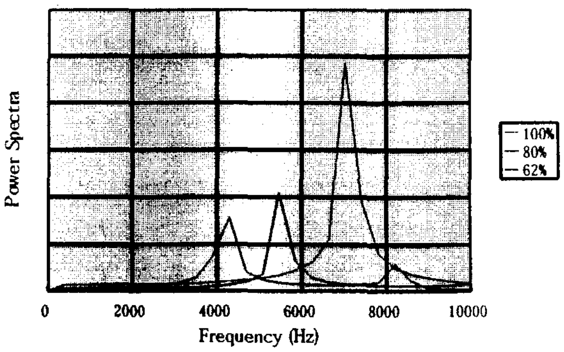


(b) Pressure histories at the pressure surface



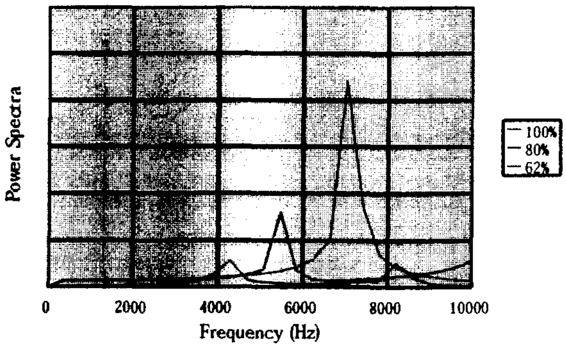
(c) Pressure histories at the suction surface

Figure 12 Unsteady pressure data



(a) Power spectra at the pressure surface

(b)



(b) Power spectra at the suction surface

Figure 13 Results of FFT analysis