DEVELOPMENT OF THE PRESSURE-SENSITIVE PAINT MEASUREMENT FOR LARGE WIND TUNNELS AT JAPAN AEROSPACE EXPLORATION AGENCY

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Keywords: *Pressure-Sensitive Paint, Temperature-Sensitive Paint, Wind Tunnel, Testing*

Abstract

JAXA's practical Pressure-Sensitive Paint (PSP) measurement system for large wind tunnels is introduced. Contents of the system which includes paint, apparatus, data processing and so on are described. Two pressure calculation methods, a-priori/in-situ hybrid and a-priori, are used in the data processing, and former one is the primary method due to its higher reliability at present.

For validating this PSP system, two experiments are conducted: an ONERA M5 standard model test in a transonic wind tunnel and a supersonic transport model test in a supersonic wind tunnel. Both PSP results were reasonable and agreed well with pressure tap data. It was proved that the present PSP system could be applied to practical tests at large transonic and supersonic wind tunnels.

The PSP data were also compared with CFD data to estimate the capability of PSP as a CFD validation tool. Through the comparison between PSP and CFD, it was confirmed that PSP had the potential to become a powerful tool to validate CFD results in detail.

1 Introduction

Pressure-sensitive paint(PSP)[1] has been used for pressure distribution measurements in wind tunnel testing since early 1990's. PSP is a non-intrusive optical pressure measurement technique. It is applied from low-speed[2-4] to hypersonic[5] flow fields. In particular, it has mainly applied to transonic and supersonic wind tunnel tests. Unlike the conventional discrete pressure tap method, PSP can acquire a global surface pressure distribution by using PSP painted model and CCD camera. It can produce global, high-spatial resolution and quantitative pressure distribution results, therefore it has been becoming a useful tool for aerospace research and development activities. From the aerodynamic point of view, PSP is useful to understand the aerodynamic flow field on model surface visually. From the structural point of view, it gives the detailed surface load distribution. PSP is also attractive as a CFD code validation data.

Japan Aerospace Exploration Agency (JAXA) has constructed the practical PSP measurement system for JAXA's large productive wind tunnels. The main targets are the 2m × 2m transonic wind tunnel (TWT1) and the 1m × 1m supersonic wind tunnel (SWT1). Although extension to low-speed application is also under development[6], it is not easy because PSP is absolute pressure sensor in principle. PSP system construction for TWT1 and SWT1 has almost finished and the validation experiments in these wind tunnels were conducted. This system will be open for wind tunnel users in near future.

In this paper, the summary of JAXA's PSP measurement system and the results of validation tests in two wind tunnels are described. The accuracy of those PSP results was compared with conventional pressure tap method. Those comparisons are also introduced.

2 Pressure-Sensitive Paint Measurement

2.1 Principle of PSP

PSP measurement is a molecular sensor based optical measurement technique. Fig.1 is the schematic of PSP measurement. Illumination light is to supply the luminescent energy to PSP and CCD camera measures the luminescence intensity. PSP consists of two layers; white undercoat and active layer. Active layer is a mixture of probe molecule and oxygen permeable polymer. White undercoat is used to enhance the PSP luminescence by diffusive reflection.

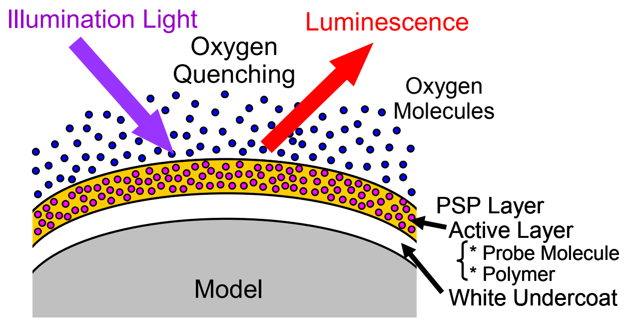


Fig.1. Schematic of PSP Measurement

The principle of PSP measurement stands on the oxygen quenching of the luminescence of pressure-sensitive probe molecule. Thus, PSP can sense the oxygen partial pressure in actual. Air includes 21% oxygen, therefore pressure value can be measured using luminescent intensity variation of PSP. Theoretically, its relation is represented by following Stern-Volmer relation;

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} \qquad (1)$$

where, I and P are the luminescent intensity and pressure of wind-on test condition and I_{ref} and P_{ref} are those of wind-off reference one. In JAXA's PSP measurement system, the universal expression of equation (1), which is quartic and includes temperature dependency on coefficients, was used to fit the relation between pressure, temperature and luminescence intensity.

2.2 Temperature Dependency of PSP

PSP has not only the pressure sensitivity but also the temperature dependency. PSP intensity and coefficients of equation (1) depend on temperature. Thus, when the pressure is calculated using PSP, it is very important to compensate the temperature effect in some way.

The simplest method is to use a thermometer. It is convenient to measure representative temperature. However, its drawback is the lack of spatial resolution. Another solution is to use an infrared (IR) camera[4]. It can measure global temperature distribution. However, the utilized wavelength of IR camera is so long that conventional glass or transparent plastic cannot transmit it. And the setting space to install IR camera in addition to CCD camera also becomes a problem. The best solution are to produce temperature-insensitive PSP, which has developed at NASA Langley[7], or PSP/TSP binary paint[8]. However, there are chemical and spectrographic difficulties on developing such ideal paints and few examples are reported.

In this study, it is handled by temperature measurement using Temperature-Sensitive Paint (TSP). One side of a test model is painted by PSP and the other is painted by TSP. Then the temperature effect of PSP is compensated by TSP data assuming symmetrical temperature distribution[9,10]. This method has the limitation of symmetrical assumption, however, one CCD camera can measure PSP and TSP at same time and no limitation on wavelength transmittance of window material.

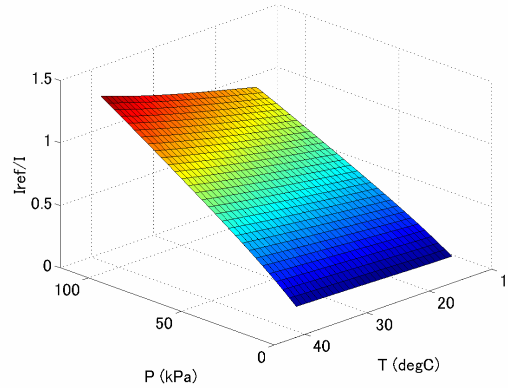
The temperature dependency of PSP is compensated using both PSP and TSP data. To solve it needs numerical iteration process. The relation between pressure, temperature, PSP data $(I_{ref}/I)_{PSP}$ and TSP data $(I/I_{ref})_{TSP}$ are represented below;

$$f\left(\frac{P}{P_{ref}}, \frac{T}{T_{ref}}\right) = f\left(\left(\frac{I_{ref}}{I}\right)_{PSP}, \left(\frac{I}{I_{ref}}\right)_{TSP}\right) \qquad (2)$$

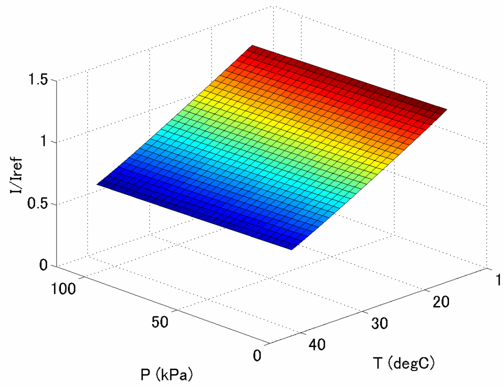
To resolve equation (2), PSP and TSP characteristic surfaces are necessary. They are shown in Fig.2 in next section.

2.3 PSP and TSP

JAXA's standard PSP consists of platinum(II) meso-tetra(pentafluorolphenyl) porphine (PtTFPP) as probe molecule and poly(isobutylmethacrylate-co-trifluoroethylmethacrylate) (poly(IBM-co-TFEM)) as oxygen permeable polymer, and those of Temperature-Sensitive Paint (TSP) is dichlorotris(1,10-phenanthroline)-ruthenium(II) hydrate (Ru(phen)) as probe molecule and polyurethane. Polyurethane is a gas impermeable polymer because Ru(phen) has not only temperature sensitivity but also pressure dependency. Fig.2 is the PSP and TSP characteristic surfaces against pressure and temperature. Reference condition of these characteristics is 100kPa and 25°C. The vertical axis of PSP is expressed by I_{ref}/I and that of TSP is I/I_{ref}. PSP has large pressure sensitivity, 0.85kPa/%, and temperature dependency, 1.3°C/%. TSP has large temperature sensitivity, 2.4%/°C, and small pressure dependency, 0.07%/kPa.



(a)



(b)

Fig.2. Pressure and Temperature Characteristics of PSP and TSP (I_{ref}=25°C, 100kPa); (a) PSP, (b) TSP

2.4 Measurement Apparatus

Fig.3 is the PSP measurement setup at TWT1. There are three sets of CCD camera and illumination. They correspond to upper measurement system and side one. Side measurement system consists of both of left and right system. Because a test model is painted PSP and TSP symmetrically, upper system can measure both PSP and TSP side at the same time, however, side system needs 2 sets of CCD camera and illumination to measure PSP side and TSP one at the same time.

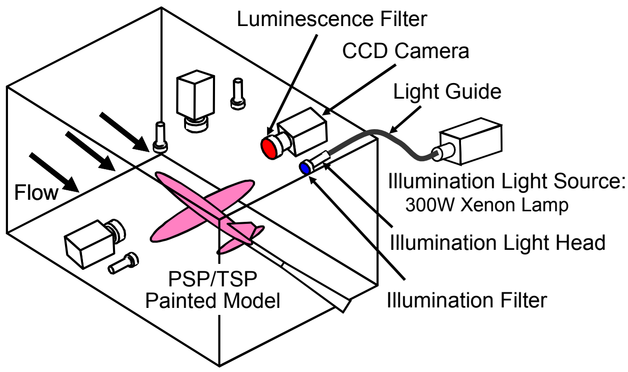


Fig.3. Components of the PSP Measurement System

Major components of PSP measurement apparatus are illumination light source, image acquisition device and optical filters. Contents of each component are described below.

Illumination Light Source

300W Xenon lamp with stabilizing circuit is used as the illumination light source to supply energy to PSP and TSP. The output illumination light is transmitted to the illumination light head through a light guide. The light guide is used to handle the light transmission easily. The illumination light head is lens system to illuminate a PSP painted model. There are two types of the illumination light head in JAXA's system, which are the standard illumination light head and the wide one. The standard one illuminates the area of ϕ=500mm at 1m from its exit. The wide one illuminates the area of ϕ=1300mm at 1m. Appropriate one is selected depending on the measurement area.

Image Acquisition Device

The CCD cameras are used to detect the luminescence intensity from PSP and TSP. It is necessary to have high signal-to-noise (S/N) ratio and high quantum efficiency because the PSP and TSP luminescence intensity are small. To increase S/N ratio, our CCD cameras are slow-scan and cooled (up to -60°C) type. There are two types of CCD camera used in JAXA's system. One is interline CCD cameras with micro-lens, and the other is full-frame-transfer ones. Both of them have more than 50% quantum efficiency. The resolution of their analog-to-digital converter is 14 bit.

Optical Filters

The PSP and TSP luminescence is much smaller than illumination light intensity. Thus, it is necessary to eliminate the illumination light from CCD camera image. Optical filters are installed in front of the illumination light head (illumination filter) and CCD camera (luminescent filter). The illumination filter transmits only the wavelength of violet and blue, which corresponds to the absorption wavelength of probe molecule of PSP and TSP. The luminescent filter transmits only the wavelength of red, which corresponds to the luminescence wavelength of PSP and TSP.

2.5 Wind Tunnel Test Sequence

At the beginning of a day, the reference images are acquired. These reference images are taken under known pressure and temperature. If there are multiple wind-on test cases, it is necessary to acquire all reference images corresponding to wind-on test cases. For each case, it is better to acquire a lot of images to increase the S/N ratio. CCD camera image has the shot noise on it. It is a quantum noise. To decrease the shot noise, the essential mean is to increase the number of electron stored on CCD device. One of the methods to increase electron is to acquire multiple images. It is taken 5-10 images and decreased the ratio of shot noise. In addition to acquire reference images, dark images also need to acquire. Each CCD device has its own dark current characteristics. Thus, this dark component should be subtracted from all CCD camera images using these dark images.

After the acquisition of reference images, the wind tunnel starts and wind-on test images are acquired. It is also better to acquire a lot of images on each case. In the continuous wind tunnel PSP test, it is possible to acquire a lot of images because the phenomena are almost stable. However, in a blow-down wind tunnel test, it is not possible to average the multiple images because the model temperature varies during flow duration.

2.6 Data Processing

PSP image acquired by CCD camera are the map of luminescence intensity. These images are converted to quantitative pressure images through data processing. JAXA's PSP data processing software[11] is constructed using MATLAB® on Windows PC. It has been designed to be suitable to process effectively large test cases of practical PSP tests. All information to analyze each test case is described on an input file. Data processing is automatically progresses along this input file. Its outline is described below.

Preprocessing

Preprocessing includes the image averaging and dark image subtraction. Image averaging is one mean to decrease the shot noise and increases the S/N ratio. And dark component of CCD camera image needs to subtract from all CCD camera images using dark image. This is dark image subtraction.

And spatial filter to reduce shot noise, for example, wiener filter, is also applied on these images.

These preprocessing is common for both PSP and TSP data.

Image Registration

To calculate pressure value using PSP, it is necessary to make the ratio image. It is the map of I_{ref}/I for PSP or I/I_{ref} for TSP. The model location on CCD camera image between wind-on and wind-off is different because a test model is deformed by aerodynamic force during wind-on condition. Thus, an image processing to align wind-on deformed image to wind-off reference one is necessary. It is the image registration. The markers on a model are utilized as reference points for this alignment to fix the image transformation function from wind-on image to reference one. Then whole of the wind-on image is transformed using this function. Then PSP and TSP ratio image are constructed.

JAXA's PSP data processing software is now under reconstruction from image base (1st generation) to 3D grid base (2nd generation). In the 2nd generation software, both of reference and wind-on image are mapped on 3D grid at first using the image transformation function and then the ratio between reference and wind-on value is calculated on each grid point.

Pressure Calculation

After construction of the PSP and TSP ratio image, pressure value is calculated by equation (2). Temperature compensation of PSP is included implicitly. To solve equation (2) is numerical iteration process, thus Newton-Raphson method is used to enhance the convergence.

The detail of pressure calculation is described following section 2.7. In JAXA's software, there are two methods, *a-priori* and *a-priori/in-situ* hybrid, to calculate pressure from PSP and TSP ratio data. Present primary method for practical application is *a-priori/in-situ* hybrid method which uses pressure tap data to improve accuracy. In contrast to *a-priori/in-situ* hybrid method, *a-priori* method needs no pressure tap. This method tends to be affected by various error sources. However, its simplicity of test models and instruments is useful because pressure distribution can be acquired using PSP painted force model without pressure tap. Thus, both of *a-priori/in-situ* hybrid and *a-priori* method are used in parallel now.

Post Processing

Post processing includes the display of the pressure map, the comparison between PSP and pressure tap, and so on. In the image base 1st generation software, 3D mapping processing is performed here.

2.7 Pressure Calculation Methods

Calibration between pressure and luminescence intensity is necessary to transfer camera image to pressure and temperature map. There are two conventional PSP calibration methods, *a-priori* and *in-situ*. In JAXA's system, *a-priori* and *a-priori/in-situ* hybrid method is used in parallel. *A-priori/in-situ* hybrid method is one of the modified *in-situ* methods.

The details of JAXA's *a-priori* and *a-priori/in-situ* hybrid method are described below.

***A-priori* Method**

A-priori method is a pressure calculation method using an off-line PSP and TSP calibration. This calibration uses the PSP and TSP sample coupon which have same characteristic with a test model. Fig.4 is the schematic of the JAXA's *a-priori* method. Before the wind tunnel test, PSP characteristics are calibrated using automatic calibration stand shown in Fig.5 which can set the matrix of the discretionary pressure and temperature calibration points. The calibration results were shown in Fig.2. Pressure value is calculated by equation (2) using PSP and TSP data and PSP and TSP characteristic surfaces.

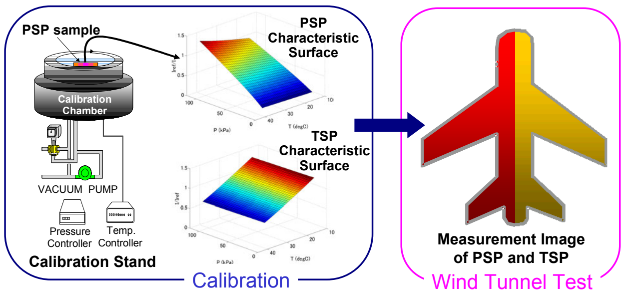


Fig.4. Schematic of *a-priori* method

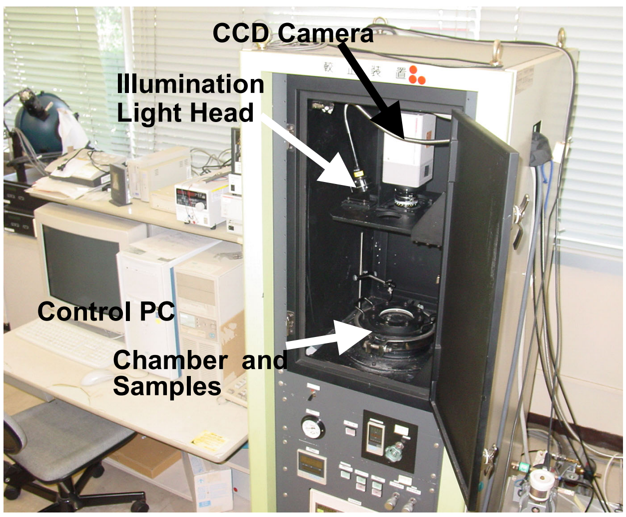


Fig.5. Automatic Calibration Stand at JAXA

Final target of JAXA's PSP system is *a-priori* method. *A-priori* method is attractive that it needs no pressure taps on the test model and pressure test can be conducted using force test model. However, *a-priori* method is easily affected various factor, for example, intensity variation of illumination light, error on compensated temperature, PSP photo degradation, etc. The data accuracy of *a-priori* method is slightly less than that of *in-situ* methods.

A-priori/In-situ Hybrid Method

Before description about *a-priori/in-situ* hybrid method, it is mentioned about conventional *in-situ* method briefly. *In-situ* method is an on-site calibration which makes the relationship between pressure tap data and corresponding PSP intensity data simultaneously. Fig.6 is the schematic of conventional *in-situ* method. Conventional *in-situ* method is widely used for practical PSP tests because it can produce high accuracy data due to introduction of pressure tap data.

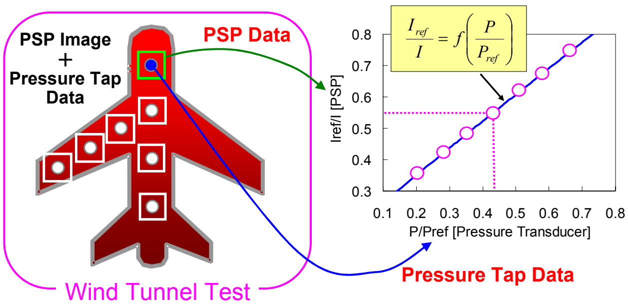


Fig.6. Schematic of Conventional *In-situ* Method

However, conventional *in-situ* method calibrates the PSP characteristics from given pressure tap data. Depending on the arrangement of pressure tap, there is region which local pressure exceeds the range of pressure taps. *In-situ* method has the possibility of such extrapolation. In addition, PSP characteristic has non-linearity. Quadratic or cubic expression gives better fitting than linear one. However, it is danger to calculate pressure on such extrapolation using quadratic or cubic expression. An example is observed on the lower surface of the wing. The pressure distribution is almost uniform. Extrapolation problem is appeared around pylon or fairing where shock wave is generated and there are local high pressure peak.

To improve such extrapolation effect and keep high accuracy due to introduction of pressure tap data, *a-priori/in-situ* hybrid method is employed as primary pressure calculation method in JAXA's system. It is one of modified *in-situ* methods. There is a similar methods reported by Woodmansee et al[12]. However, their accuracy was inferior to conventional *in-situ* method on their paper because it assumes uniform temperature distribution. *A-priori/in-situ* hybrid method includes temperature distribution compensation. The essences of this method are;

- compensate PSP's temperature dependency and TSP's pressure dependency using PSP and TSP data in a mutually complementary manner
- introduction of the correction coefficient to compensation global unknown error source

The first point is introduced by painting PSP and TSP symmetrically. The correction coefficient of second point is introduced by the comparison PSP data with pressure tap data. The formulation of *a-priori/in-situ* hybrid method is following;

$$f\left(\frac{P}{P_{ref}},\frac{T}{T_{ref}}\right)=f\left(\left(\frac{I_{ref}}{C_{PSP}\cdot I}\right)_{PSP},\left(\frac{C_{TSP}\cdot I}{I_{ref}}\right)_{TSP}\right) \tag{3}$$

where, C_{PSP} is the correction coefficient of PSP data and C_{TSP} is the correction coefficient of TSP data. If there are no thermometers to compare with TSP data, C_{TSP} is assumed as 1.

Equation (3) is necessary to calculate by numerical iteration using PSP and TSP characteristic surface shown in Fig. 2. The correction coefficient C_{PSP} and C_{TSP} are evaluated on every iteration process for all pressure taps. An averaged value of them is used as the correction coefficient on certain iteration routine.

This *a-priori/in-situ* hybrid method can compensate global error source, for example, intensity variation of illumination light, PSP and

TSP global characteristic variation, and so on. However, it cannot treat local error source.

3 Results and Discussion

3.1 ONERA M5 Standard Model Test at the Transonic Wind Tunnel

Test Model

ONERA M5 model was used for the PSP validation experiment at the JAXA 2m × 2m transonic wind tunnel(TWT1). Fig.7 is the PSP/TSP painted ONERA M5 model. This model is a standard model of TWT1. Its wing span is 0.982m and fuselage length is 1.058m. PSP (PtTFPP+poly(IBM-co-TFEM)) was applied on the starboard side and TSP (Ru(phen)+ polyurethane) was applied on port side to compensate the temperature dependency with supposition of the symmetrical flow field. There are 133 pressure taps on whole model and pressure was measured with three Scanivalve pressure scanners. Two pressure tap lines on wing indicated on Fig.8 were used to evaluate the PSP data.

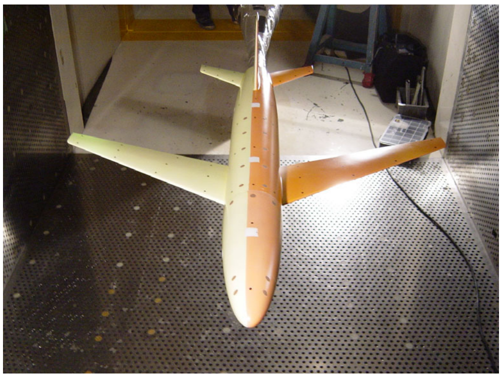


Fig.7. PSP/TSP Painted ONERA M5 Model
Port Side(pink): PSP
Starboard Side(yellow): TSP

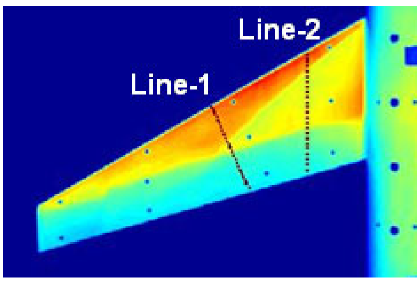
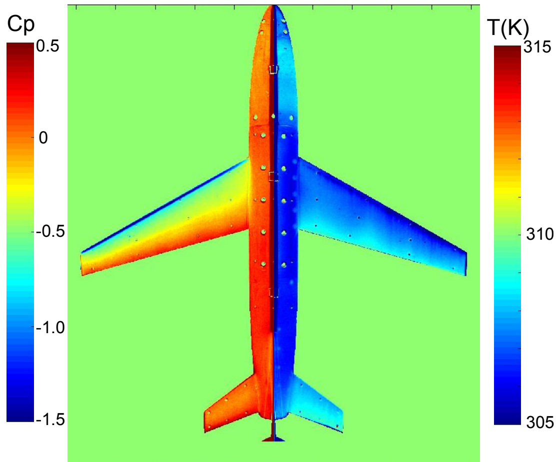


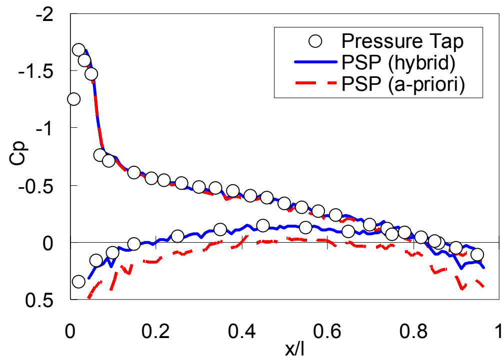
Fig.8. Pressure Tap Lines on ONERA M5 Model

Experimental Results

Fig.9 and 10 are the examples of the PSP results of TWT1. Fig.9s are the results of M=0.6 and Fig.10s are those of M=0.84. Fig.9 (a) and Fig.10 (a) are the pressure and temperature distribution. Pressure value was calculated using



(a)



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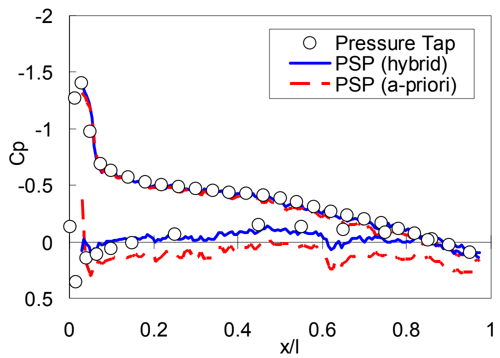

(c)

Fig.9. ONERA M5 PSP Results
(M=0.6, α =0.3°, q=19.8kPa, Ps=78.5kPa)
(a) Pressure and Temperature Distribution on Upper Surface; Left-Hand Side: Cp, Right-Hand Side: Temperature (b) Comparison between PSP, Pressure Tap and CFD, Line-1, (c) Line-2

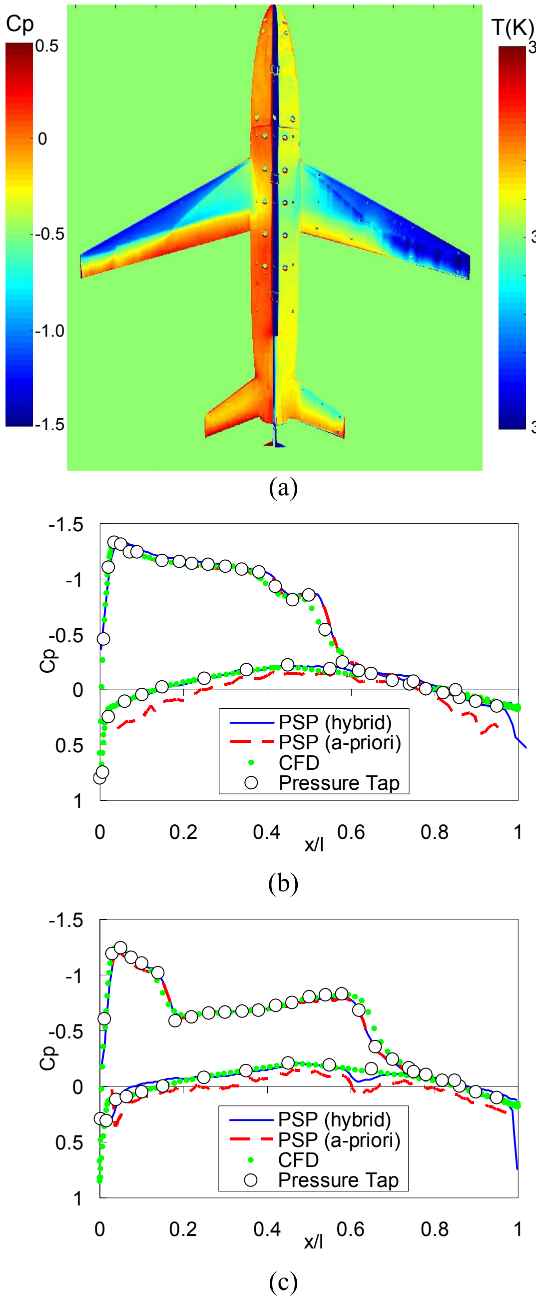

Fig.10. ONERA M5 PSP Results
(M=0.84, α =0.6°, q=31.1kPa, Ps=62.9kPa)
(a) Pressure and Temperature Distribution on Upper Surface; Left-Hand Side: Cp, Right-Hand Side: Temperature (b) Comparison between PSP, Pressure Tap and CFD, Line-1, (c) Line-2

a-priori/in-situ hybrid calibration. About pressure distribution, the PSP has produced the global pressure distribution image. Pressure distribution on the wing on Fig.9 (a) is almost 2-dimensional toward the wing span. On Fig.10 (a), complex flow field which has multiple shock wave system that is two-stage at inner wing and single shock wave at outer wing is observed. And it is also recognized that the low pressure region on the wing extents on the fuselage. The detailed flow field structure on whole model surface is easily understood by PSP data even in a complex flow field in the case of Fig.10 (a).

From the temperature distribution on Fig.9 (a) and Fig.10 (a), there was the temperature distribution that was order of several °C. It would be caused by the adiabatic wall temperature and the model structure like the thickness of local model part. These temperature distributions are too large to assume uniform temperature in order to use conventional *in-situ* or some other methods. If it is possible to takes long time to get uniform temperature distribution, its uniformity would be improved, however, it spoils wind tunnel data productivity. Thus, the temperature distribution compensation used in *in-situ/a-priori* hybrid and *a-priori* methods is necessary for high-productivity practical, which means short interval during test cases, wind tunnel tests.

Fig.9 (b), (c) and Fig.10 (b), (c) are PSP data comparison with pressure tap data. There are two types of PSP results, *in-situ/a-priori* hybrid and *a-priori* methods on them. The results of *in-situ/a-priori* hybrid method are good agreement with pressure tap data on both of upper and lower surfaces. The maximum discrepancy is less than Cp=0.1. However, about the results of *a-priori* method, data of upper surface is good agreement with pressure tap, however, the data of lower surface has discrepancy with pressure tap data. The data of upper surface and lower surface were acquired in different cases. There would be any error sources on the case of lower surface. One of the possible error sources is PSP characteristic aging due to experienced temperature. It has been observed on sample tests. It might be long term hysteresis of PSP. *A-priori* method is affected these error sources, however *in-situ/a-priori* hybrid method had the compensation function due to pressure tap even in the existence of such phenomena.

PSP for CFD Code Validation

Because a PSP measurement produces a global and quantitative pressure data, it is also attractive for CFD code validation data. By using conventional pressure taps, CFD code validation was limited discrete points or lines. It means that the confirmation is limited only some local area. The confirmation on limited area cannot extrapolate to another area. However, PSP is global measurement, therefore CFD code can be validated all over the model. And its information density is higher than CFD grid. Fig.11 is a PSP and CFD[13] comparison on ONERA M5 model. Global agreement of both data was good. There were some discrepancies on the region around wing-body junction and rear fuselage. At the wing-body junction, the configuration of the suction region was different with each other and the pressure level of rear fuselage was difference. The shock wave location at the wing tip was also different. These evaluations became possible due to PSP data. On the Fig. 10 (b), (c), CFD results are also drawn. It was good agreement with PSP (hybrid) and pressure tap data. PSP data can compare with CFD at each point quantitatively.

These are only one example of PSP data application as the CFD validation data, however, it can be confirmed that PSP has the large potential to validate CFD in detail.

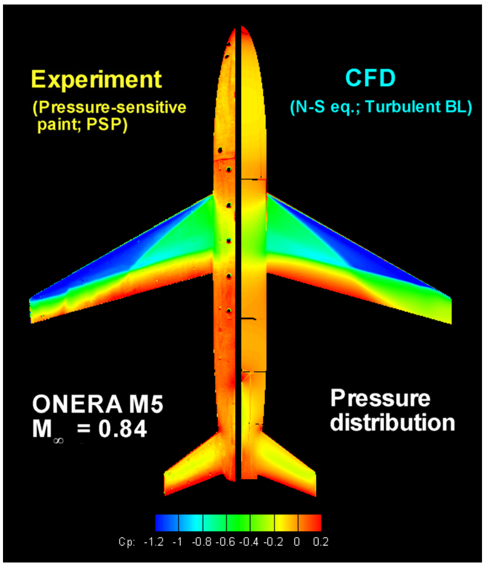

Fig.11. PSP and CFD Comparison
(M=0.84, α=0.6 °, Re=1.7M)
Left-Hand Side: PSP, Right-Hand Side: CFD

3.2 SST Model Test at the Supersonic Wind Tunnel

Test Model

A PSP validation experiment was also conducted using a supersonic transport(SST) configuration model at the JAXA 1m × 1m supersonic wind tunnel (SWT1). The test model shown in Fig.12 was 8.5% scale model of JAXA's SST experimental configuration. PSP (PtTFPP+poly(IBM-co-TFEM))was applied on the port side of the model, and TSP (EuTTA+PMMA) was applied on the starboard side. The thickness of paint is 30-60 micrometers at PSP and 50-110 micrometers at TSP. There are 108 pressure taps on whole model surface and 5 pressure taps lines on the wing. On Fig.13, 4 lines on wing, y/(b/2)=0.15, 0.3, 0.5, 0.7, were used to compare the PSP result with pressure tap data (the pressure scanner was ZOC).

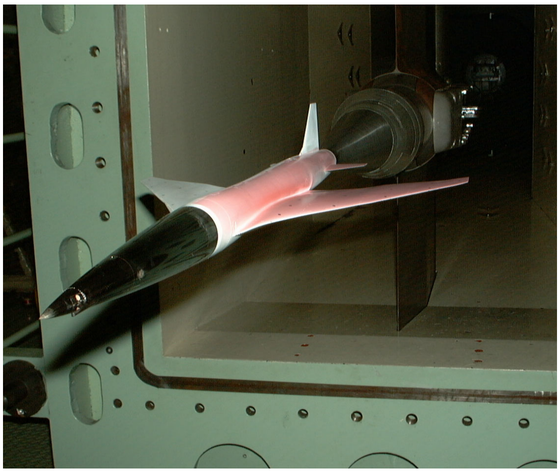

Fig.12. 8.5%-Scale SST Model
Port Side: PSP (pink), Starboard Side: TSP (white)

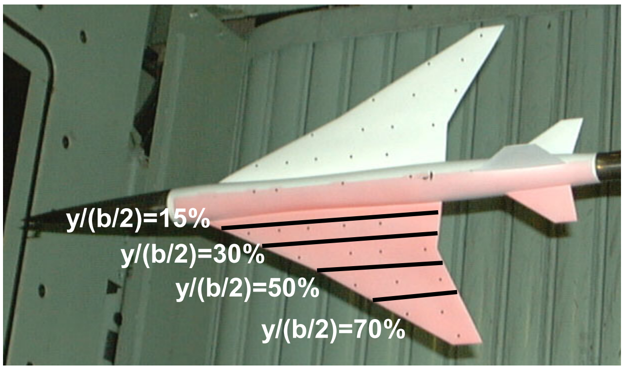

Fig.13. Pressure Tap Lines on SST Model

Experimental Results

Fig.14 is an example of the PSP results of SWT1 test. Pressure was calculated using only *a-priori* calibration in this case. From global pressure image, the suction region on the leading edge caused by leading edge vortex was clearly acquired. Its detailed configuration and location is understood visually. Fig.14 (b)-(e) are the data comparison between PSP and pressure taps. PSP results are good agreement with pressure tap data. There were some regions where their difference is rather large around the leading edge suction region. The reason of this difference seemed to be caused by the high temperature gradient at the wing leading edge region. It is observed on temperature image on Fig.14 (a). Small temperature difference between both wings made the inconsistency of the temperature compensation and caused pressure error. However, the maximum discrepancy between PSP and pressure taps was within Cp=0.03. It corresponds to 2.4kPa. The repeatability between different 2 PSP test cases was also good.

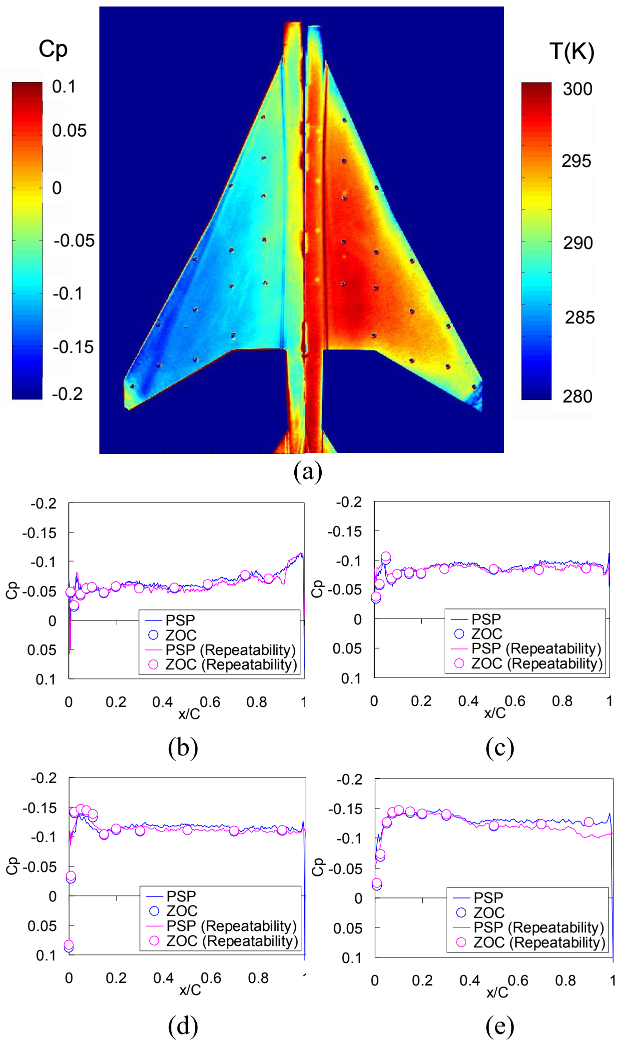

Fig.14. SST Model PSP Results on Leeward Surface (M=2.0, α=2°, q=78.4kPa, Ps=27.8kPa)
(a) Pressure and Temperature Distribution; Left-Hand Side: Cp, Right-Hand Side: Temperature (b) Comparison between PSP and Pressure Tap data, y/(b/2)=0.15, (c) y/(b/2)=0.3, (d) y/(b/2)=0.5, (e) y/(b/2)=0.7

4 Conclusion

Details of the JAXA's practical PSP measurement system for large wind tunnels were introduced. The characteristics of PSP/TSP paint, measurement system, and contents of the data processing were described. At the present, the primary method to calculate pressure value in data processing is *a-priori/in-situ* hybrid method, which introduces pressure tap data to improve data accuracy of conventional *a-priori* methods. *A-priori* method, which needs no pressure taps on test model, is also used due to its simplicity of test models and instruments.

Experiments for validating the present PSP measurement system were conducted at 2m × 2m transonic wind tunnel (TWT1) and 1m × 1m supersonic wind tunnel (SWT1). The results indicated that the PSP data by the system could give global and detailed quantitative pressure distribution. It was proved that the error of the PSP in comparison with pressure taps was less than Cp=0.1 at TWT1 test and Cp= 0.03 at TWT1. In particular, results of the *a-priori/in-situ* hybrid method showed good agreement with pressure tap data. It was confirmed that PSP could be applied to practical test at large transonic and supersonic wind tunnels.

PSP also has large potential as a CFD validation tool. Comparison between PSP and CFD gives a lot of information about problems and challenges of CFD. Global, high-spatial resolution and quantitative PSP data are useful to validate CFD result in detail.

PSP measurement, which has both visual information and quantitative pressure value, is a powerful tool for aerodynamic design and research, structural analysis, CFD code validation and so on.

Aknowledgement

The authors gratefully acknowledge Mr. Shigeya Watanabe, Mr. Masatake Ito and Mr. Takuro Hashimoto for their contribution to whole of the PSP system development and the members of JAXA Transonic Wind Tunnel Team and Supersonic Team for their support to the PSP wind tunnel tests, in particular, Dr. Norikazu Sudani and Mr. Akira Koike. The authors would like to thank Mr. Jyunichi Mukai and Dr. Kazuomi Yamamoto for providing their CFD results of ONERA M5 model.

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