JOURNAL OF AIRCRAFT
Vol. 43, No. 5, September–October 2006

Temperature Correction of Pressure-Sensitive Paint for Industrial Wind Tunnel Testing

Mitsuru Kurita,* Kazuyuki Nakakita,† Kazunori Mitsuo,* and Shigeya Watanabe‡
Institute of Aerospace Technology, Japan Aerospace Exploration Agency, Chofu, Tokyo 182-8522, Japan

DOI: 10.2514/1.13608

Pressure-sensitive paint measurement can obtain a much more detailed surface pressure distribution than can be obtained using conventional pressure taps. However, the pressure-sensitive paint is sensitive not only to pressure but also to temperature, and where high accuracy is required, it is essential to compensate for this temperature dependency. This paper discusses data processing methods for pressure-sensitive paint measurement in transonic industrial wind tunnel testing, and proposes three methods to compensate for temperature dependency of the pressure-sensitive paint: an in situ method, an a priori method, and a hybrid of a priori and in situ methods. The pressure distributions from the pressure-sensitive paint data obtained by these proposed methods are compared with pressure tap data measured by conventional pressure transducers, and it is confirmed that the proposed methods are effective in compensating the temperature dependency of pressure-sensitive paint and improve the accuracy of the obtained data. It is also found that the hybrid of a priori and in situ methods is widely applicable to the industrial wind tunnel testing even if the pressure range of the pressure tap data is limited.

Nomenclature

C_p = pressure coefficient
C_{PSP} = compensation constant for PSP data
C_{TSP} = compensation constant for TSP data
f, g = functions of pressure ratio and temperature ratio
I = luminescence intensity
M = Mach number
p = pressure
T = temperature
x/c = airfoil chordwise coordinate measured from leading edge, normalized by chord
α = angle of attack
σ = standard deviation

Subscripts

PT = pressure tap location
ref = reference condition in wind tunnel testing
refc = reference condition at calibration
TM = thermometer location
0 = stagnation condition
∞ = freestream conditions

Introduction

PRESSURE-SENSITIVE paint (PSP) measurement gives global surface pressure distributions on model in wind tunnel testing. Because PSP measurement is effective for predicting aerodynamic loads and validating computational fluid dynamics (CFD), there is a growing demand for PSP measurement in industrial wind tunnels. By providing much more detailed pressure distribution information than conventional pressure tap measurements, PSP measurement effectively provides the design process with a comprehensive insight into the flowfield and can contribute to shortening the development term of airplanes and aerospace vehicles [1].

However, PSP is sensitive not only to pressure but also to temperature [2–6], and PSP data reduction methods that do not compensate for this temperature dependency yield reduced measurement accuracy. Compensation for this temperature dependency of PSP has been one of the most critical issues to be resolved for achieving the accurate data.

Previous studies have discussed several methods to compensate for the temperature dependency of PSP. The "*K-fit* calibration" [3] corrects the changes of PSP luminescence intensity with temperature change by a single coefficient, K, which is obtained based on the assumption that surface temperature distribution over the wind tunnel test model is isothermal. *K-fit* calibration is particularly useful with ideal paints in situations where the range of pressures measured by pressure taps does not span the range encountered by the paint [2]. However, it is not applicable when the wind tunnel test model is nonisothermal because the PSP's temperature dependency over the entire model is corrected using only one coefficient.

Another method, "temperature-corrected pressure calibration" [3], prepares a set of PSP calibration curves, each obtained at constant representative temperatures. Pressure at an arbitrary temperature is then calculated by the linear interpolation of the calibration curves. This method has the advantage that the nonisothermal effect in the wind-on condition is compensated by using local temperature data obtained via temperature-sensitive paint (TSP) or by other temperature measurement techniques. However, further correction is required to reduce systematic errors such as the instability of the incident illumination intensity [2].

In wind tunnel testing, the wind tunnel test model is generally far from isothermal condition because the attitude of model and the freestream Mach number are changed frequently to obtain as much data as possible within a limited test period. Moreover, it is not always possible for the wind tunnel test model to have a sufficient number of pressure taps covering an adequate pressure range to calibrate the PSP. Therefore, to make PSP measurement effective for these applications, a calibration method is required that can be applied even if the wind tunnel test model has some temperature distribution, limited pressure taps, and unknown systematic errors. In this study, three new calibration methods to compensate for the temperature dependency of PSP are proposed and evaluated.

Presented as Paper 2189 at the 24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, Portland, OR, 28 June–1 July 2004; received 28 January 2005; revision received 31 January 2006; accepted for publication 23 February 2006.

*Researcher, Wind Tunnel Technology Center, 7-44-1 Jindaiji-Higashi. Member AIAA.
†Associate Senior Researcher, Wind Tunnel Technology Center, 7-44-1 Jindaiji-Higashi. Member AIAA.
‡Senior Researcher, Wind Tunnel Technology Center, 7-44-1 Jindaiji-Higashi. Senior Member AIAA.

Outline of the Proposed PSP Measurement

The first method for calibrating the temperature dependency of PSP is an in situ method [3,7,8] that uses temperature distribution data obtained by TSP to compensate for error due to the effect of the PSP's temperature dependency. The second is an a priori method [3,7] that uses the pressure- and temperature-dependent characteristics of both the PSP and the TSP. The third is a hybrid of a priori and in situ methods that corrects systematic errors of the PSP and TSP luminescence intensity in wind tunnel tests by introducing an in situ compensation constant calculated using pressure tap data and model temperature data measured by thermometers.

In this study, a wind tunnel test model was painted with both PSP and TSP. The latter is used for the compensation of the PSP temperature dependency as described next. The PSP was applied on the port side of the model, whereas the TSP was applied on the starboard side (see Fig. 1). The dyes employed were Pt(II)meso-Tetra (Penta-fluorophenyl)Porphine (PtTFPP) for the PSP, and Dichlorotris(1,10-phenanthroline)-ruthenium(II)hydrate [Ru(phen)] for the TSP [5]. Because the angle of sideslip was set to zero, it is assumed that the surface pressure and temperature distributions on the starboard and port sides of the model are symmetric. This assumption is effective when model internal structural differences that cause temperature difference between the starboard and port sides of the model are negligible. If the dual-luminophor coating technique [6] were used, the proposed data reduction methods would be applicable to models at nonzero angle of sideslip, because it does not require assumption of symmetry.

Flowcharts of data processing that include the proposed calibration methods are shown in Fig. 2. For all three methods, the first stage is a preprocessing shown in Fig. 2a. In the first step of the preprocessing, averaged dark images with no illumination are subtracted from both averaged wind-off and wind-on images. In the second step, because aerodynamic loads during wind tunnel runs (wind-on) move and deform the model slightly from the wind-off location and shape, the wind-on image is transformed to match the wind-off image geometrically using a process usually known as "image registration" [9,10] to reduce errors due to nonuniformity of the paint coating, including matching the outline of model in the images. Black markers placed on the model surface (the black dots on the model in Fig. 1) are used to detect the location of the model for the image registration. After image registration as the third step, the ratios between the wind-off and wind-on luminescence intensities are calculated. The TSP luminescence intensity ratio on the starboard side of the model is reflected about the model's centerline to determine the temperature in the PSP-painted area on the port side, assuming a symmetric temperature distribution as mentioned. Finally, as second stage shown in Fig. 2b–2d, the luminescence intensity ratio distributions of the PSP and TSP are transformed to pressure and temperature distributions by one of the calibration methods. The second stage of the data processing is described in detail in the next section.

Calibration Methods

Conventional Calibration Methods

The PSP characteristic is theoretically represented by the Stern–Volmer relation [2,8],

$$\frac{I(p_{\mathrm{ref}}, T_{\mathrm{ref}})}{I(p, T)} = A(T) + B(T)\frac{p}{p_{\mathrm{ref}}} \tag{1}$$

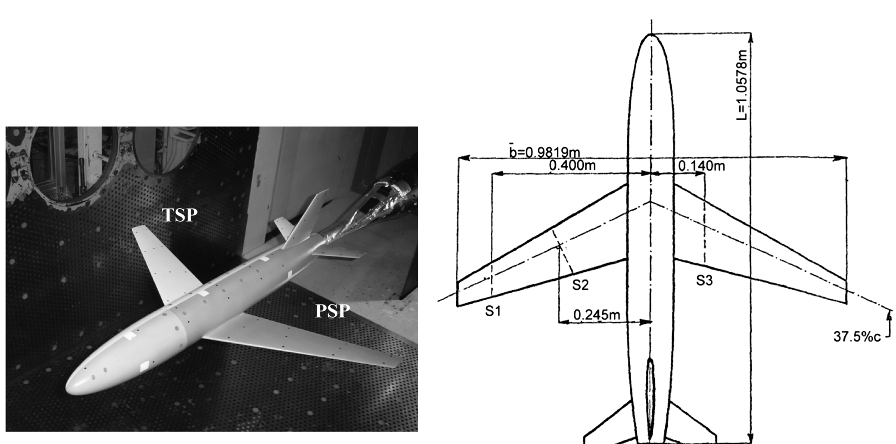
A and B are functions of temperature and are determined by calibration. The subscript "ref" represents a reference condition at a known pressure and temperature. By measuring the luminescence intensity at a known (or estimated) temperature, the pressure can be obtained using Eq. (1).

There are two categories of calibration method for the PSP characteristics: an in situ method and an a priori method. These are described in the following two sections.

In Situ Method

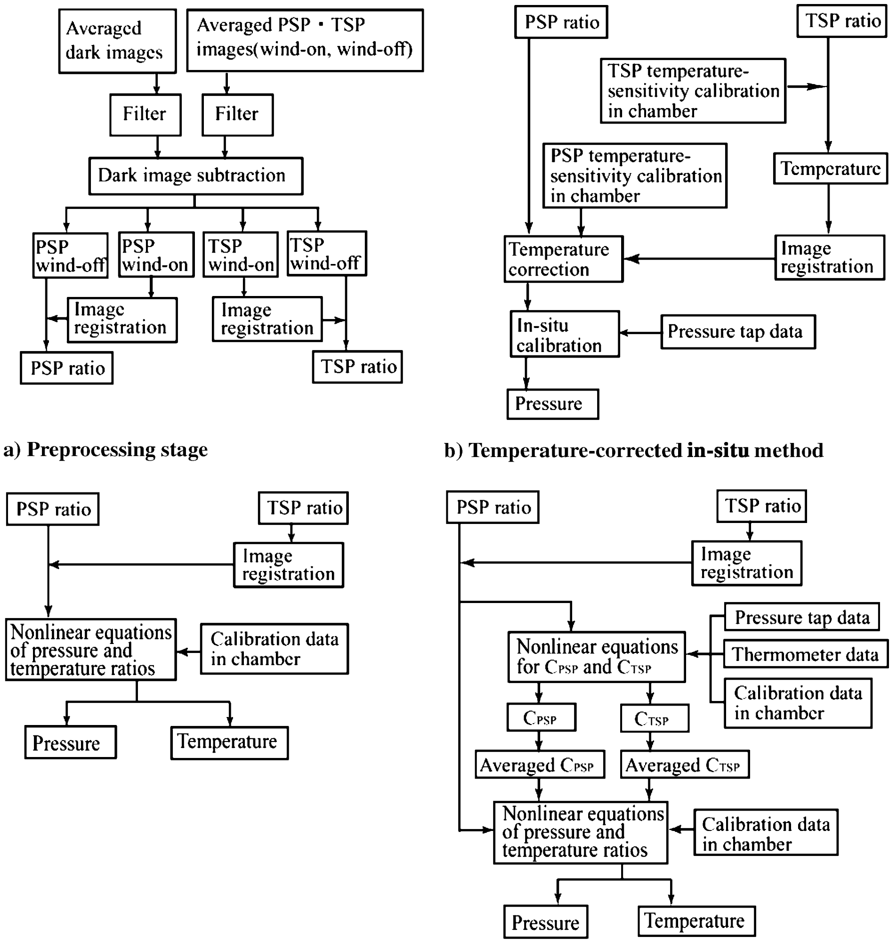
An in situ method is an on-site calibration method that obtains the relationship between the pressures measured by conventional pressure transducers connected to pressure taps and the luminescence intensities of the PSP around the corresponding pressure taps [2–4]. Although a reasonable number of pressure taps are necessary on the model surface, which is the most significant drawback of the in situ method, in situ method has been widely used for PSP measurement because it can produce high accuracy data. In situ method has another advantage in that it can compensate for error caused by instability of the incident illumination intensity [8]. However, if the pressure range obtained by the pressure taps is insufficient (i.e., does not cover the pressure range experienced by the PSP during wind tunnel measurement), PSP pressure data beyond the pressure tap data range have some error in the extrapolation of the calibration curve due to the nonlinearity of the PSP characteristic. This is the primary limitation of the in situ method.

In the conventional in situ method, temperature changes on the model are assumed to be either negligible or strongly correlated with the pressure change. If this assumption is true, error due to PSP temperature dependency can be compensated [7]. However, if the temperature distribution on a model is not negligible, the luminescence intensity of the PSP will change locally due to its temperature dependency even under uniform pressure conditions and as a result, the pressure data obtained from the PSP luminescence intensity will show scatter around the pressure tap data, indicating that proper temperature-dependency compensation is needed for the in situ method.



a) Photograph of model **b) Dimension of model**

Fig. 1 Wind tunnel test model, ONERA M5.



a) Preprocessing stage **b) Temperature-corrected in-situ method**

c) Temperature-corrected a-priori method **d) A-priori/in-situ hybrid method**

Fig. 2 Flow chart of data processing.

A Priori Method

In the conventional a priori method, the pressure and temperature dependency of the PSP are measured using PSP-painted sample plates in a calibration chamber before wind tunnel tests [2,3]. In this study, a similar calibration was also carried out for the TSP. The luminescence intensity of TSP decreases according to the increase in temperature, and this characteristic is represented by an empirical equation [4,6].

Both the sample plates and the wind tunnel test model are painted simultaneously using the same lot of paints to minimize error due to differences in paint characteristics between the samples and the model. The luminescence intensities of the PSP and TSP obtained in wind tunnel testing are then transformed to pressure and temperature distribution data using the calibration data.

The main advantage of a priori method is that, in contrast to the in situ method, the model does not need any pressure taps. On the other hand, there is a significant disadvantage that the accuracy of the PSP data is strongly affected by error factors such as instability of the incident illumination intensity [2] between the wind-on and wind-off conditions, and changes in PSP characteristics between calibration and wind tunnel testing.

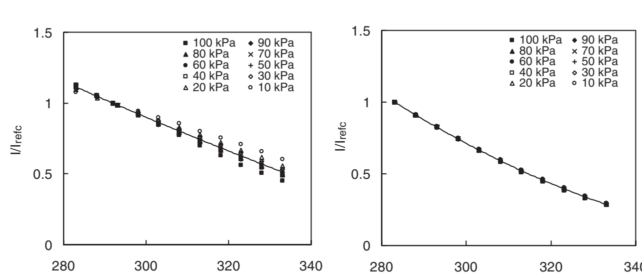
Proposed Calibration Methods

Temperature-Corrected In Situ Method

In general, a wind tunnel test model is not isothermal during wind tunnel testing, and so the conventional in situ method, which assumes that temperature is uniform over the model's surface, is not suitable for obtaining accurate pressure data.

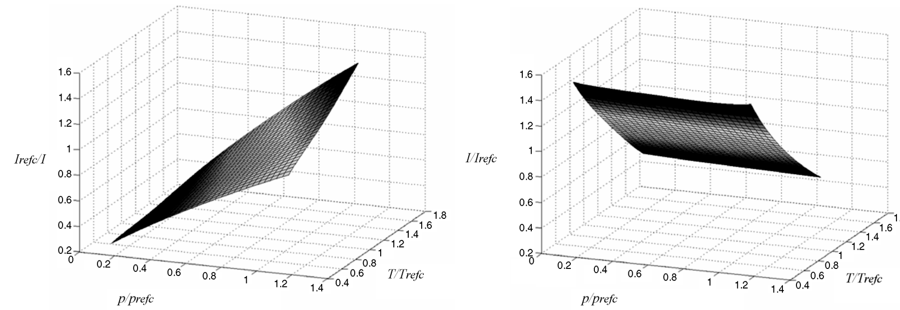
This study proposes an in situ calibration method (shown in Fig. 2b) that can be used even if the model is not isothermal by correcting the PSP temperature dependency using temperature distribution data obtained via TSP. Figures 3a and 3b, respectively, show the temperature-sensitivity characteristics of the PSP and TSP in this study obtained using a calibration chamber. Second-order polynomials are employed as approximate calibration curves. The effects of pressure on the temperature sensitivity of the PSP and TSP are neglected here, meaning that the temperature sensitivity of the PSP and TSP are assumed to be constant over a pressure range of 10 to 100 kPa. Under this assumption, the temperature distribution of the model can be measured by using only TSP data.

Based upon both the temperature distribution on the model obtained via TSP and the temperature-dependency data of PSP shown in Fig. 3a, the PSP luminescence intensity ratio obtained during wind tunnel testing is corrected to a value in isothermal (i.e., wind-off) conditions, $I(p_{\mathrm{ref}}, T_{\mathrm{ref}})/I(p, T_{\mathrm{ref}})$,



a) PSP, T_{refc} = 291.9 [K] **b) TSP, T_{refc} = 283.1 [K]**

Fig. 3 Temperature sensitivity of PSP and TSP characteristics.



a) PSP **b) TSP**

Fig. 4 Calibration surfaces of PSP and TSP characteristics, $p_{\mathrm{refc}} = 100$ kPa, $T_{\mathrm{refc}} = 30.0\,^{\circ}$C.

$$\frac{I(p_{\mathrm{ref}}, T_{\mathrm{ref}})}{I(p, T_{\mathrm{ref}})} = \frac{I(p_{\mathrm{ref}}, T_{\mathrm{ref}})}{I(p, T)} \frac{I(p, T)}{I(p, T_{\mathrm{refc}})} \frac{I(p, T_{\mathrm{refc}})}{I(p, T_{\mathrm{ref}})} \tag{2}$$

where the first term of the right-hand side is obtained from the wind tunnel test result whereas the second and third terms are obtained from the PSP temperature-sensitivity data measured in the calibration chamber.

After this transformation to correct the luminescence intensity ratio change due to changes of the model temperature, the PSP luminescence intensity ratio $I(p_{\mathrm{ref}}, T_{\mathrm{ref}})/I(p, T_{\mathrm{ref}})$ becomes a function that depends only on pressure. Therefore, the relationships between pressure tap data and the temperature-corrected PSP luminescence intensity ratio data around the corresponding pressure taps can be treated by the conventional in situ method.

Temperature-Corrected A Priori Method

An a priori method to compensate for the temperature dependency of the PSP (shown in Fig. 2c) is described here. The luminescence intensity ratios of PSP and TSP are represented as functions (f and g) of pressure ratio and temperature ratio.

$$\mathrm{PSP:}\ \frac{I_{\mathrm{refc}}}{I} = f\left(\frac{p}{p_{\mathrm{refc}}}, \frac{T}{T_{\mathrm{refc}}}\right) \tag{3}$$

$$\mathrm{TSP:}\ \frac{I}{I_{\mathrm{refc}}} = g\left(\frac{p}{p_{\mathrm{refc}}}, \frac{T}{T_{\mathrm{refc}}}\right) \tag{4}$$

where the subscript "refc" denotes the reference condition in the a priori calibration. In the data processing, f and g in Eqs. (3) and (4) are approximated by fourth-order polynomials based on a priori calibration chamber data. Figure 4 shows the surfaces approximating the sensitivity characteristics of the PSP and TSP on pressure and temperature ratios. As can be seen, the PSP is sensitive to both pressure and temperature, whereas the TSP has temperature sensitivity and relatively small pressure sensitivity.

To calculate the pressure and temperature distributions on the wind tunnel test model, the luminescence intensity ratios of the PSP and TSP at the wind-off condition in the wind tunnel testing are transformed to the ratios at the calibration reference condition, "refc," using the calibration surfaces [2], and the transformed ratios are substituted into Eqs. (3) and (4). Therefore, Eqs. (3) and (4) become equations of two unknowns, i.e., the pressure ratio p/p_{refc} and the temperature ratio T/T_{refc}. The pressure ratio and the temperature ratio are then directly obtained by solving these nonlinear equations.

A Priori/In Situ Hybrid Method

This is a method that can be applied even if the pressure tap data do not cover a sufficient pressure range and that can compensate for unknown systematic errors, which is shown in Fig. 2d.

To correct the systematic errors, in situ compensation constants are introduced that are applied to the luminescence intensities of PSP and TSP in the wind-on conditions [5]. That is, systematic errors in the luminescence intensity ratios of PSP and TSP are corrected by in situ compensation constants, C_{PSP} for PSP and C_{TSP} for TSP, as shown in the following equations:

$$\mathrm{PSP:}\ \frac{1}{C_{\mathrm{PSP}}} \frac{I_{\mathrm{refc}}}{I} = f\left(\frac{p}{p_{\mathrm{refc}}}, \frac{T}{T_{\mathrm{refc}}}\right) \tag{5}$$

$$\mathrm{TSP:}\ C_{\mathrm{TSP}} \frac{I}{I_{\mathrm{refc}}} = g\left(\frac{p}{p_{\mathrm{refc}}}, \frac{T}{T_{\mathrm{refc}}}\right) \tag{6}$$

When both C_{PSP} and C_{TSP} are equal to unity, Eqs. (5) and (6) are identical to Eqs. (3) and (4), respectively.

These constants are calculated using both the pressure tap data and the model temperature data measured using thermometers installed near the model surface. As shown in Eqs. (7–10), the PSP and TSP data for calculating the constants are taken only around the pressure taps and the thermometers, assuming symmetry.

PSP around pressure tap:

$$(1/C_{\mathrm{PSP}})(I_{\mathrm{refc}}/I)_{\mathrm{PT}} = f(p_{\mathrm{PT}}/p_{\mathrm{refc}}, T_{\mathrm{PT}}/T_{\mathrm{refc}}) \tag{7}$$

TSP around pressure tap:

$$C_{\mathrm{TSP}}(I/I_{\mathrm{refc}})_{\mathrm{PT}} = g(p_{\mathrm{PT}}/p_{\mathrm{refc}}, T_{\mathrm{PT}}/T_{\mathrm{refc}}) \tag{8}$$

PSP around thermometer:

$$(1/C_{\mathrm{PSP}})(I_{\mathrm{refc}}/I)_{\mathrm{TM}} = f(p_{\mathrm{TM}}/p_{\mathrm{refc}}, T_{\mathrm{TM}}/T_{\mathrm{refc}}) \tag{9}$$

TSP around thermometer:

$$C_{\mathrm{TSP}}(I/I_{\mathrm{refc}})_{\mathrm{TM}} = g(p_{\mathrm{TM}}/p_{\mathrm{refc}}, T_{\mathrm{TM}}/T_{\mathrm{refc}}) \tag{10}$$

In these equations, subscripts PT and TM indicate data around the pressure tap and thermometer, respectively. C_{PSP} is assumed to be identical at the locations of both pressure taps and thermometers, whereas C_{TSP} is also assumed to be identical in the same way.

Because the luminescence intensity ratios, the pressure tap data $p_{\mathrm{PT}}/p_{\mathrm{refc}}$, and the thermometer data $T_{\mathrm{TM}}/T_{\mathrm{refc}}$ in Eqs. (7–10) are known, the four equations have four unknowns, i.e., $p_{\mathrm{TM}}/p_{\mathrm{refc}}$, $T_{\mathrm{PT}}/T_{\mathrm{refc}}$, C_{PSP}, and C_{TSP}, and so these unknown values can be obtained by solving the nonlinear equations. The values of C_{PSP} and C_{TSP} are obtained by averaging data calculated at pressure tap and thermometer locations. In cases without thermometer data, C_{PSP} is obtained from Eqs. (7) and (8), where C_{TSP} is fixed to unity. Finally, the entire pressure and temperature distributions of the wind tunnel test model are obtained by substituting the averaged C_{PSP} and C_{TSP}, respectively, to Eqs. (5) and (6) and solving the nonlinear equations in a similar way to the a priori method.

Wind Tunnel Tests to Evaluate the Proposed Calibration Methods

Experimental Setup

To evaluate the proposed calibration methods, wind tunnel tests were conducted in the Japan Aerospace Exploration Agency's 2 × 2 m transonic wind tunnel using an ONERA M5 transport-type standard wind tunnel test model. Figure 1a shows the model installed

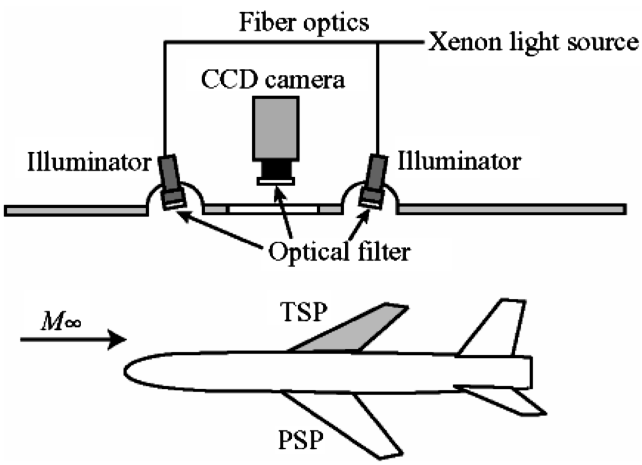


Fig. 5 PSP measurement system.

in the test section of the wind tunnel and its dimensions are presented in Fig. 1b. The angle of attack range was from −1 to 3 deg with zero angle of sideslip. The freestream Mach number M_∞ was set at 0.84 and 0.92 and stagnation pressure p_0 was set to 100 kPa.

Both the PSP and the TSP were applied over a white base coat to increase the effective luminescence intensity by reflection in the paint layer. To evaluate the measurement accuracy of the PSP, the pressure distribution on the model's surface was also measured by pressure taps along several lines using conventional pressure transducers.

Figure 5 shows a schematic of the PSP measurement system [5]. This consists of an incident illumination system and a 14-bit CCD camera with optical filters for instrumentation. PSP and TSP image data for the upper and lower surfaces of the model were obtained by the camera by setting the roll angle of the wind tunnel test model to 0 and 180 deg.

Results and Discussion

Figure 6 shows typical pressure and temperature distributions on the model's upper surface at Mach number 0.92 at zero angle of attack. The increase in pressure due to shock waves is clearly observed on the main wing. Two shock waves occur on the inboard main wing and merge into a single shock wave on the outboard main wing. The temperature increase downstream of the shock waves on the main wing is also observed. Moreover, a low-pressure region on the fuselage due to the aerodynamic interaction between the main wing and the fuselage can be observed, although some error due to a self-illumination effect are included. The information on the flowfield obtained from the pressure distribution via PSP is significantly more detailed than that obtained by the conventional pressure tap data.

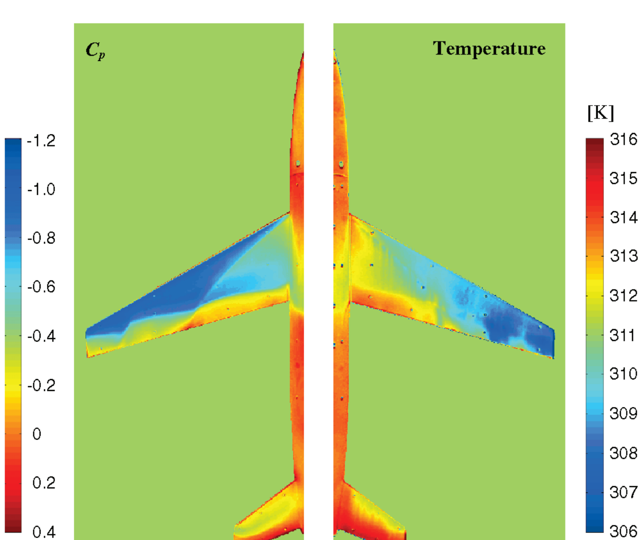
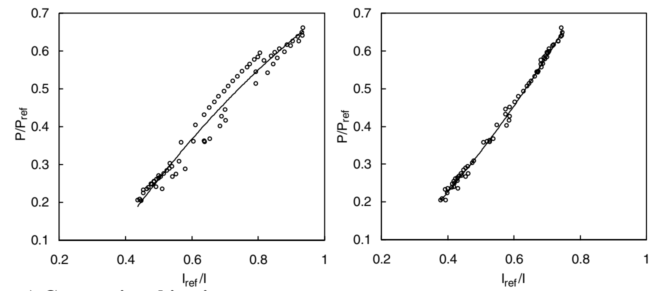


Fig. 6 Pressure and temperature distribution by a priori/in situ hybrid method: $M_\infty = 0.92$, $\alpha = 0$ deg.



a) Conventional in-situ method **b) Temperature-corrected in-situ method**

Fig. 7 Calibration curve: $M_\infty = 0.84$, $\alpha = 0$ deg.

Comparison Between the Temperature-Corrected and Conventional In Situ Methods

To evaluate the effectiveness of the temperature-dependency correction by the proposed in situ method, wind tunnel test results obtained using the proposed in situ method are compared with the results obtained using the conventional in situ method, which neglects the PSP temperature dependency.

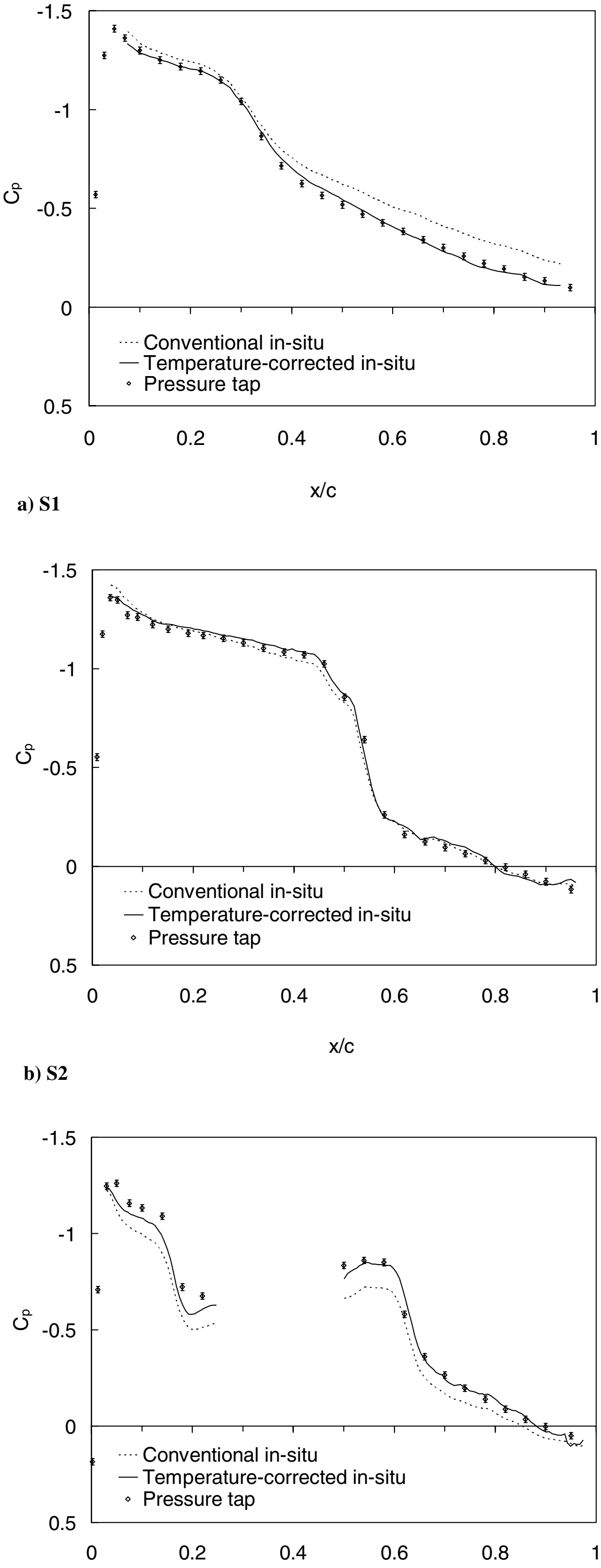
Figure 7a shows the calibration curve of the conventional in situ method. The pressure taps employed here are located along three lines on the upper surface of the main wing. The pressure tap data at Section 3 (S3) on the TSP side of the model is also employed because the pressure and temperature distributions of the model can be assumed to be symmetric at zero angle of sideslip. Because the temperature distribution on the wing upper surface is not uniform due to the increase in temperature downstream of the shock wave, the PSP data from the conventional in situ method do not correlate well with the pressure tap data.

Figure 8 shows the pressure distributions of the main wing upper surface at the three sections, S1, S2, and S3, based on the calibration curve from the conventional in situ method. The PSP data processed by the conventional in situ method do not agree well with the pressure tap data due to the scatter observed in the calibration result (Fig. 7a). The error bars of the pressure tap data shown in this figure are estimated from the uncertainty levels of the pressure transducers connected to the pressure taps and the stagnation and static pressures of the wind tunnel freestream. The data for the S3 line at $x/c = 0.25$–0.5 are not shown in Fig. 8c because they have the local error due to the nonuniform intensity distribution of the incident illumination.

Figure 7b shows a calibration curve of the proposed in situ method, where the temperature dependency of the PSP is corrected. The difference between the pressure tap data and PSP data in the calibration curve of the proposed in situ method is estimated as a standard deviation of $\sigma = 0.95$ kPa, whereas with the conventional in situ method $\sigma = 2.61$ kPa. The pressure distribution data obtained by the proposed in situ method are compared with the data by the conventional in situ method in Fig. 8. The data by the proposed in situ method are in much better agreement with the pressure tap data, demonstrating the effectiveness of the PSP temperature-dependency correction.

Comparison Between the Temperature-Corrected A Priori and In Situ Methods

The pressure distributions obtained by the proposed temperature-corrected a priori and in situ methods are compared in Fig. 9. The results of the proposed a priori and in situ methods are almost identical for the upper surface of the main wing. However, on the lower surface, there is a systematic quantitative bias between the PSP data and the pressure tap data in the results of the temperature-



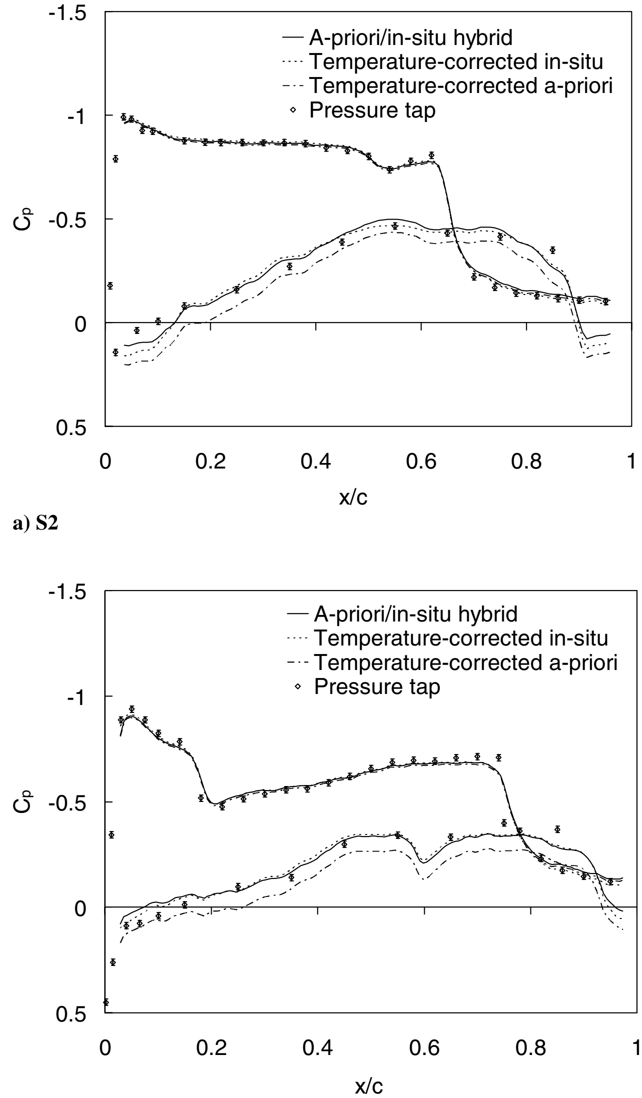
a) S1

b) S2

c) S3

Fig. 8 Pressure distribution on main wing: $M_\infty = 0.84, \alpha = 0$ deg.

corrected a priori method, although qualitative agreement with the pressure tap data is shown. Whereas the source of this error has not been identified, it might be caused by instability of the incident illumination intensity or changes in the PSP characteristics (e.g., due



a) S2

b) S3

Fig. 9 Pressure distribution on main wing: $M_\infty = 0.92, \alpha = 0$ deg.

to photodegradation). In terms of standard deviation, the difference between the pressure tap data and PSP data in the pressure coefficient of the proposed a priori method is estimated to be $\sigma = 0.054$, compared with $\sigma = 0.037$ for the proposed in situ method.

These results indicate that the proposed a priori method is inferior in accuracy to the proposed in situ method. However, the in situ method has a limitation in that it requires pressure tap data covering a sufficient pressure range. Figure 10 shows a typical result for the case where the pressure tap data range is insufficient for the proposed in situ method. Here, pressure tap data for $x/c > 0.5$ are intentionally omitted from the calibration to examine the effect of the pressure tap data range on the performance of the proposed in situ method. As a result, data for the high-pressure region around the trailing edge have significant error due to extrapolation of the nonlinear calibration curve.

Comparison of the A Priori/In Situ Hybrid Method with Other Methods

The results using the proposed a priori/in situ hybrid method are compared with the results using the other methods in Fig. 9. C_{TSP} was set to unity in this study because a thermometer installed in the wind tunnel test model was not be able to measure the surface temperature due to the model's large heat capacity.

The results of the proposed a priori/in situ hybrid method on the upper surface of the main wing show good agreement with pressure tap data. Moreover, the results for the lower surface show that the

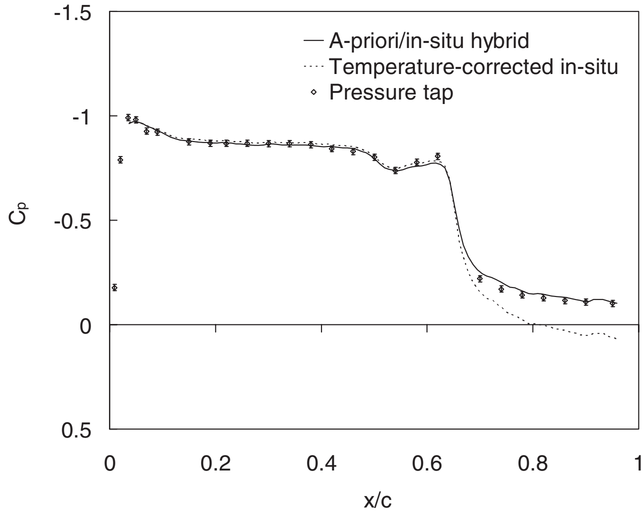


Fig. 10 Pressure distribution on main wing at S2 intentionally omitting pressure tap data in $x/c > 0.5$ from calibration $M_\infty = 0.92, \alpha = 0$ deg.

differences between the PSP data and pressure tap data observed in the proposed a priori method are well corrected by the a priori/in situ hybrid method. The difference between pressure tap data and PSP data in the pressure coefficient calculated by the proposed a priori/in situ hybrid method is estimated as a standard deviation $\sigma = 0.032$.

Comparing the proposed in situ and a priori/in situ hybrid methods in Fig. 9, both show good agreement with the pressure tap data because pressure tap data that cover a sufficient pressure range are used. To confirm the effect of the calibration pressure range obtained by the pressure taps, Fig. 10 shows a case in which pressure tap data for $x/c > 0.5$ are omitted from the calibration of both the a priori/in situ hybrid method and proposed in situ method. The results of the a priori/in situ hybrid method show reasonable agreement with the pressure tap data, even when the range of pressure of pressure tap data employed is narrower than the whole pressure range of the PSP. This result suggests that the a priori/in situ hybrid method is widely applicable to industrial wind tunnel testing.

Conclusions

Three PSP calibration methods, temperature-corrected in situ, temperature-corrected a priori, and a priori/in situ hybrid methods, were developed and evaluated in this paper. The conclusions from this study are summarized as follows:

1) The temperature-corrected in situ method can give a calibration curve with relatively small data scatter even if the model has some temperature distribution. As a result, if there are pressure tap data covering a sufficient pressure range, the temperature-corrected in situ method improves the data accuracy of the PSP relative to the conventional in situ method that ignores the temperature distribution on the model.

2) The temperature-corrected a priori method can obtain pressure and temperature data directly by solving the nonlinear equations without pressure tap data. However, this method is significantly affected by error sources such as photodegradation and incident illumination intensity change, resulting in large measurement errors.

3) The a priori/in situ hybrid method can compensate for the systematic bias error inherent in the conventional and the proposed a priori methods, and is effective even if the pressure range of the pressure tap data is narrow relative to the whole pressure range over the model. Based on the evaluation results of the three methods, the a priori/in situ hybrid method, which has highest accuracy and robustness, is considered to be the most widely applicable to industrial wind tunnel testing.

Acknowledgments

The authors would like to gratefully thank Masatake Ito and Takuro Hashimoto for their contributions to the PSP system construction and wind tunnel tests. Special thanks go to Makoto Ueno for discussions about the software and to members of JAXA WINTEC Transonic Wind Tunnel Section for supporting the wind tunnel tests.

References

[1] Jordan, J. D., Watkins, A. N., Fleming, G. A., Leighty, B. D., Schwartz, R. J., Ingram, J. L., Grinstead, K. D., Oglesby, D. M., and Tyler, C., "Rapid Technology Assessment via Unified Deployment of Global Optical and Virtual Diagnostics," *Proceeding of the Twentieth International Congress on Instrumentation in Aerospace Simulation Facilities*, Institute of Electrical and Electronics Engineers, Piscataway, NJ, Aug. 2003, pp. 190–201.

[2] Bell, J. H., Schairer, E. T., Hand, L. A., and Mehta, R. D., "Surface Pressure Measurements Using Luminescent Coatings," *Annual Review of Fluid Mechanics*, Vol. 33, Jan. 2001, pp. 155–206.

[3] Woodmansee, M. A., and Dutton, J. C., "Treating Temperature-Sensitivity Effects of Pressure-Sensitive Paint Measurements," *Experiments in Fluids*, Vol. 24, No. 21998, pp. 163–174.

[4] Shimbo, Y., Noguchi, M., and Makino, Y., "Blowdown Tunnel Application of Pressure Sensitive Paint," AIAA Paper 99-3169, June 1999.

[5] Nakakita. K., Kurita, M., and Mitsuo, K., "Development of the Pressure-Sensitive Paint Measurement for Large Wind Tunnels at Japan Aerospace Exploration Agency," International Council of the Aeronautical Sciences Paper 2004-3.2.2., Aug. 2004

[6] Mitsuo, K., Asai, K., Hayasaka, M., and Kameda, M., "Temperature Correction of PSP Measurement Using Dual-Luminophor Coating," *Journal of Visualization*, Vol. 6, No. 3, 2003, pp. 213–223.

[7] Mébarki, Y., and Cooper, K. R., "Aerodynamic Testing of a Generic Automotive Model with Pressure Sensitive Paint," *Proceeding of the Tenth International Symposium on Flow Visualization*, F0120, The Visualization Society of Japan, Tokyo, Aug. 2002.

[8] Le Sant Y., Bouvier, F., Mérienne, M.-C., and Péron, J.-L., "Low Speed Tests Using PSP at ONERA," AIAA Paper 2001-0555, Jan. 2001.

[9] Le Sant, Y., "A Model Deformation Method Applied to PSP Measurements," *Proceeding of the Twentieth International Congress on Instrumentation in Aerospace Simulation Facilities*, Institute of Electrical and Electronics Engineers, Piscataway, NJ, Aug. 2003, pp. 95–104.

[10] Kurita, M., Nakakita, K., Mitsuo, K., and Watanabe, S., "Data Processing of Pressure-Sensitive Paint for Industrial Wind Tunnel Testing," AIAA Paper 2004-2189, June 2004.