JOURNAL OF AIRCRAFT
Vol. 42, No. 4, July–August 2005

Pressure-Sensitive Paint Measurements in a Blowdown Wind Tunnel

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A methodology to correct for temperature effects on pressure-sensitive paint data in a blowdown wind tunnel has been suggested. PSP measurements using Optrod-B1 paint were made on an aircraft model instrumented with thermocouples and conventional pressure taps. The tests were made at freestream Mach numbers of 0.6 and 0.8 and at model incidences of 6 and 10 deg. The temperature correction is based on a mean model temperature concept for a given blowdown and the corrected PSP data are validated using pressure port data. It has been found that the accuracy of temperature-corrected PSP results is about as good as for those obtained at transonic speeds in other tunnels elsewhere.

Nomenclature

C_p	=	model surface pressure coefficient
I	=	luminescence intensity
I_0	=	intensity at reference conditions
I_R	=	normalized intensity ratio $[I/I_0]_{\text{red}}/[I/I_0]_{\text{blue}}$
L	=	length of the model
M	=	Mach number
p	=	pressure
q	=	freestream dynamic pressure
T_1, T_2, T_3	=	model temperature at different locations, °C
T_m	=	mean model temperature, °C
T_a	=	ambient temperature, °C
$T_{0\infty}$	=	settling chamber temperature, °C
X	=	distances along the model length from the nose, m
Y	=	distance along the span, from the model centerline, m
α	=	model incidence angle, deg
ϕ	=	model roll angle, measured from symmetry plane on the top or lee surface of the wing, deg

Introduction

MEASUREMENT of surface pressures using pressure sensitive paint (PSP) is in an advanced stage of development; a few groups have been successful in using this technique to estimate overall aerodynamic loads on complex aircraft models,[1–3] as an alternative to the conventional balance technique. Excellent reviews on the subject have been published by Crites,[4] by Liu et al.,[5] and recently by Bell et al.[6]

Although the advances in the area of pressure-sensitive paints are significant, effects due to detector noise, temperature changes, calibration errors, and pressure-mapping errors are very often found to be limiting factors with respect to the accuracy of the measurement technique.[7] Among these factors, errors due to model temperature changes during PSP data acquisition can assume importance in many wind tunnel applications.[8] In continuous wind tunnels, these errors generally remain small when wind-on and wind-off images are acquired after the model temperature has stabilized. However, limited PSP applications in blowdown wind tunnels[9,10] reveal that these errors can be significant and correction of the pressure data due to temperature effects is not straightforward. The PSP testing scenario in a blowdown wind tunnel is complex; there is a drop in stagnation temperature during wind-on data acquisition, which is reflected as a relatively smaller drop in the model surface temperature. There can be small spatial variations in model surface temperatures, too, during wind-on conditions. Specifically, the wind-off and wind-on images are not acquired at the same model temperature during a blowdown. Furthermore, if more than one set of images is acquired for a given flow condition for averaging, the wind-off and wind-on images acquired during successive blowdowns could be at lower model temperatures. Any correction method for the PSP data for temperature effects will therefore need model temperature measurement at several locations using either embedded thermocouples on the model surface[11] or a paint that is also sensitive to temperature (combined PSP/TSP paint).[9] In a recent study, Mitsuo et al.[12] utilized a dual-luminophor (PtTFPP+Rhodamine B) coating to perform both pressure and temperature measurements on a delta-wing model in a continuous wind tunnel and showed good comparison of temperature-corrected PSP data with pressure-tap data in the Mach number range of 0.55–0.70.

In this paper, a simple methodology and a rationale for temperature corrections to the PSP data in a blowdown wind tunnel based on measurement of temperatures at a few locations on the model surface are described. PSP experiments were conducted on a generic combat aircraft model instrumented with pressure ports and thermocouples. Temperature corrections to the PSP data have been made using a mean temperature hypothesis. Comparisons of temperature-corrected PSP data with port pressure have revealed good agreement, with overall accuracies comparable to those obtained in continuous tunnels.

Experiments

The experiments were conducted in the National Aerospace Laboratory's 1.2-m trisonic blowdown test facility having a square working test section of 1.2×1.2 m. The tunnel can provide Mach numbers ranging from 0.2 to 4.0 and a Reynolds number range from 8×10^6 to 60×10^6 per meter; typical blowdown duration is about 20 s.

The PSP measurements were conducted in the solid-wall test section of the tunnel with the optical access provided by the modified sidewall-mounted Schlieren window (Fig. 1). The model was supported in the vertical plane using beta stings of 6 and 10 deg to provide model incidence.

Model Configuration

Figure 2 shows geometric details of the aircraft model, which was made of high-strength steel. The wing–body model had a planform typical of a combat aircraft with constant-thickness wings having beveled leading and trailing edges, for simplicity in fabrication. The

Received 30 January 2004; revision received 27 May 2004; accepted for publication 27 May 2004.

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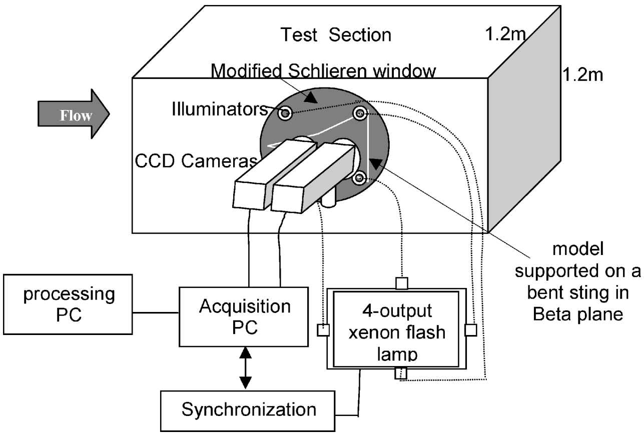
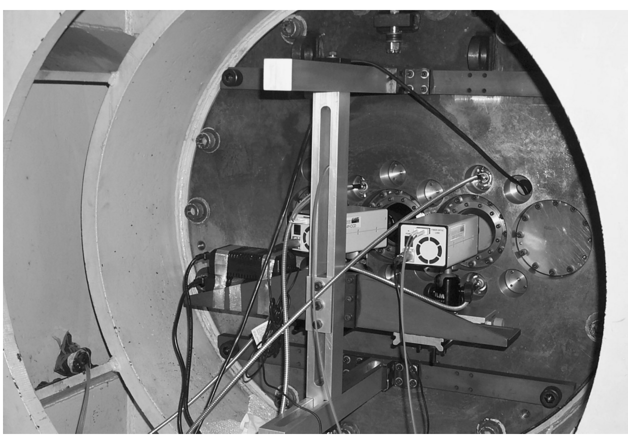


a) Schematic of PSP system



b) Photograph of the optical window with cameras and illuminator heads

Fig. 1 PSP system and details of optical access.

model, with an overall length of 430 mm and a full span of 400 mm, was instrumented with four thermocouples and a series of 14 spanwise static pressure ports (i.d. 0.8 mm) on the lee side of one of the wings, as shown in Fig. 2; three static pressure ports on the wing closer to the wing/fuselage junction were 5 mm apart and the rest were 10 mm apart. Four static pressure ports on the fuselage were located at ϕ values of 28, 40, 52, and 64 deg (12 deg apart, measured from the symmetry plane on the top surface) as shown in Fig. 2.

Flow Conditions

The PSP measurements were made at Mach numbers of 0.6 and 0.8 and angles of attack of 6 and 10 deg, using two beta stings. All the tests were conducted at a stagnation pressure of 174 kPa.

Optical Window

An existing Schlieren window metallic blank was modified to meet the requirements for PSP illumination and viewing. The window had a provision for 12 illumination locations and 4 camera viewing positions. For the present measurements, the locations of the two charge-coupled device (CCD) windows and the four illuminator positions were selected so that both the model view by the CCD cameras and the illumination on the whole model were optimized. During the tests, all the other windows were closed with dummy flanges. The CCD cameras were mounted on a three-axis support system with necessary provisions for camera alignment (Fig. 1b).

PSP Sensor and Calibration

The lee side of the model, including the fuselage and a calibration surface (a thin aluminum sheet of size 200 × 300 mm) were coated with the well-known Optrod-B1, a pyrene-based binary pressure-sensitive paint supplied by M/s Optishe Messtechnik GmbH, Germany. The binary composition requires simultaneous acquisition of an additional image, containing information about local excitation intensity (which is independent of pressure), which accounts for the instabilities of excitation light and also those arising out of model movements relative to the light source. A photograph of the coated model along with image registration markers located in the tunnel is shown in Fig. 3. The paint layer consists of a screen layer and an active layer with a total thickness of about 40 μm. Important photophysical properties of the paint are as follows:

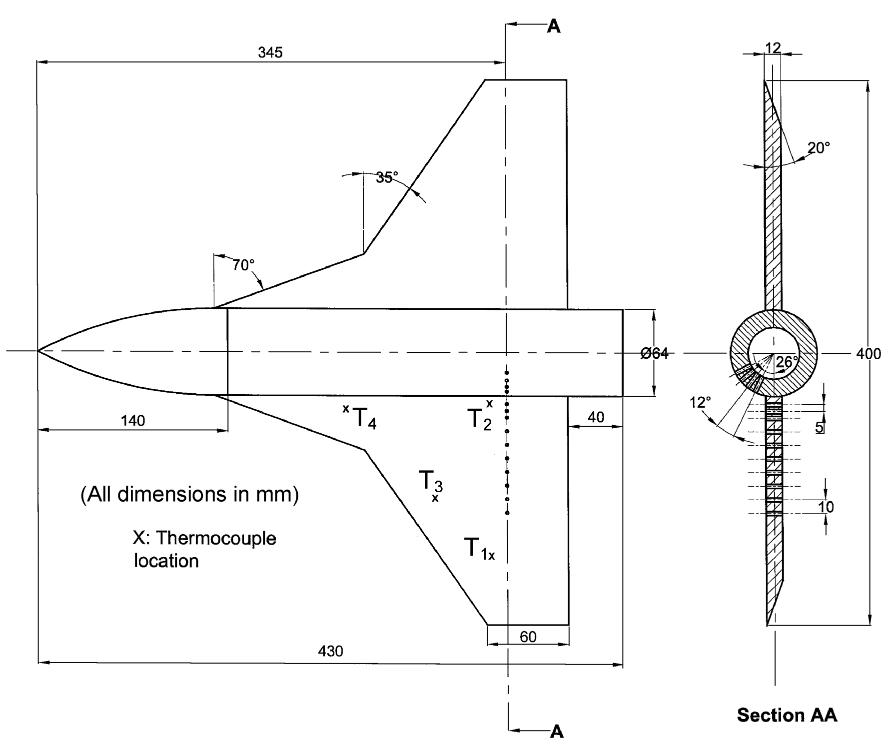


Fig. 2 Details of the aircraft wing–body model.

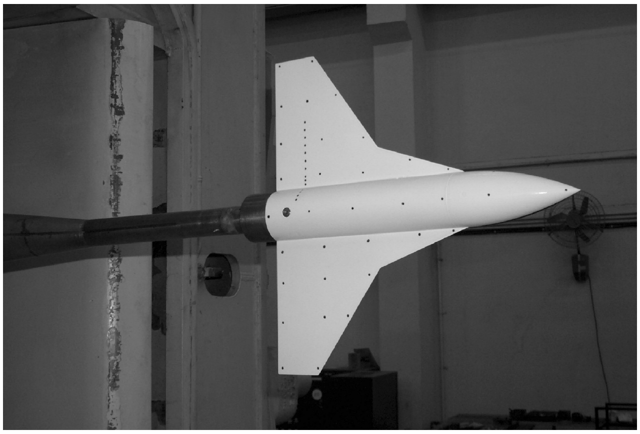


Fig. 3 Photograph of aircraft wing–body model located in the wind tunnel.

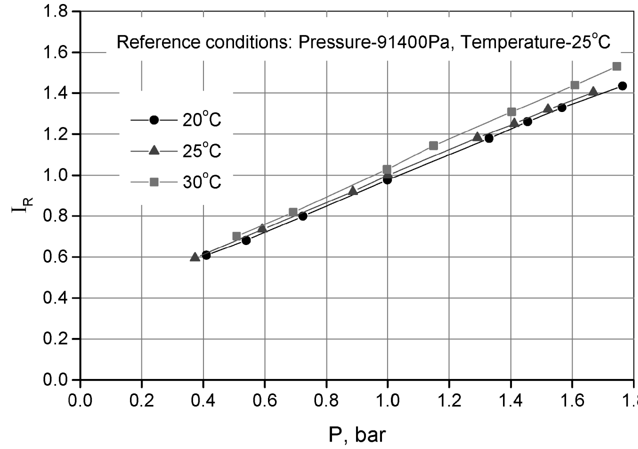


Fig. 4 Calibration of Optrod-B1 paint.

Excitation	330 ($\pm$20) nm
Pressure-sensitive emission (blue)	450–550 nm
Intensity-sensitive emission (red)	600–650 nm (excitation reference)
Temperature sensitivity	0.3 to 0.5%/°C
Pressure sensitivity	66%/bar at 25°C (nominal).

A few coupons, approximately 30×25 mm, were cut from the calibration sheet and subjected to calibration in an external calibration chamber, where an environment with controlled pressure and temperature was created. The calibration coefficients obtained for the calibration coupon were utilized for processing PSP images. The dispersion of pressure sensitivity over the calibration coupon was less than about 1% of the mean value.

The calibration chamber, made of aluminum, had dimensions of $120 \times 100 \times 75$ mm. The components of this chamber included a Peltier block (a heat exchanger along with a thermal mass), pressure and temperature sensors, a pressurizing or evacuating inlet, and a cooling circuit. The PSP sample was held to the heat exchanger (to create good thermal contact between the calibration coupon and the heat exchanger) with the help of a frame and four screws. The top plate of the chamber housed a BK-7 glass window (suitable for UV light transmission) with a viewing diameter of 50 mm. The temperature in the chamber was controlled by regulating power to the Peltier element. The maximum power required for regulation was 100 W and this was automatically controlled to obtain a measurement accuracy of about $\pm$0.5% in the range 0–60°C measured by a Peltron gauge.

The pressure regulation was achieved by evacuation or compression with the help of a vacuum/pressure pump. The pressure operating range was 0–200 kPa. The control circuit for a personal computer-based data acquisition system involved procedures for the control and measurement of temperature and pressure, triggering of cameras and lamp, and acquisition and storing of images. A LabView software incorporated these steps to carry out calibration automatically for a predetermined set of calibration parameters. Typical calibration curves of Optrod-B1 at three temperatures of 20, 25, and 30°C are shown in Fig. 4; each point on the curve is an average of four PSP images. The pressure sensitivity in the above temperature range was 64 to 68%/bar.

PSP Instrumentation and Arrangement

A state-of-the-art PSP system, well suited for transonic flow applications and based on DLR technology, was acquired recently from M/s Optishe Messtechnik (OMT) GmbH, Germany. The commissioning tests were made on a delta-wing model (DLR PSP model) in the same tunnel facility.[13]

The system consists of an UV flash lamp, two scientific-grade charge-coupled device (CCD) cameras, the calibration equipment, and an image-processing software package. Excitation of the PSP on the model was provided by a xenon flash lamp system (OMT-D40-XE), with four light guides attached to four UV antireflection-coated quartz optics, each consisting of collector and objective lenses emitting in the range of 330 ($\pm$20) nm. The lamp could be triggered externally up to 35 Hz, with single pulse duration of 20 μs. Optimum distribution of illumination on the entire model surface was obtained using four rotatable illuminator heads connected to the lamp system by four 15-m-long optical fiber cables. The paint emission data were acquired by two air-cooled scientific-grade 12-bit CCD slow-scan cameras with resolution of 1280×1024 pixels. A pressure-sensitive image in the band of 450–550 nm and an excitation reference image in the band of 600–650 nm were acquired using blue and red transparent filter sets, respectively, supplied by the OMT company.

The image acquisition was made by a personal computer-based data acquisition system based on two separate PCI cards. The camera and illumination were triggered by a NuDAQ-7230 card controlled by LabView based software in a separate computer. The final conversion of the acquired intensity images was performed by an image-processing procedure employed using OMS processing software.

Two separate cameras were used to measure the two components of the binary sensor. The image integration time (camera exposure time) was approximately 9 s for each of the pressure and the reference image (one image each acquired simultaneously from the two cameras), to have a large pixel fill ratio in the CCD array (a large signal-to-noise ratio). Therefore, in a blowdown duration of about 20 s, only one set of images could be acquired with sufficient time for flow stabilization. The sequence of measurements involved acquisition of images from the two cameras: 1) ambient pressure and temperature, 2) dark images, 3) prerun wind-off images, 4) wind-on images, and 5) postrun wind-off images. The temperature data in the settling chamber and on the model surface and the lee-surface pressures were also acquired simultaneously during the run.

An objective of focal length 12 mm was utilized in each of the cameras to provide maximum spatial resolution of PSP images, as a result, a small area of wing tip (on one of the wings) could not be imaged.

The model static pressure measurements were made using a 16-port, 10-psia ESP scanner. Four identical Cr–Al thermocouples (with a response time better than 50 ms) were utilized, which had a sensitivity of $\sim 40\mu$ V/°C and a temperature measurement accuracy of $\pm$1°C (provided by the manufacturer); experience in using these in the present PSP tests has shown that they are in fact better ($\pm$0.5–0.75°C).

Accuracy of Measured Data

The model static pressure measurements were made employing a 10-psid ESP scanner frequently calibrated during the test series. The uncertainty estimated, using the method suggested by Kline and McClintock[14] and taking into account repeatability, was $\Delta C_p < \pm 0.02 C_p$. The uncertainty in temperature measurement by Cr–Al thermocouples was observed to be less than $\pm$1°C.

Image Processing and Temperature Correction Methodology

The process of converting the intensity images to pressure plots involves a number of steps (Fig. 5) such as inputs from calibration, image alignment, ratioing, filtering, and finally mapping to the model geometric coordinates. In theory, the ratioing procedure requires the model to be in the same position before and during the blowdown and both cameras to view the model identically. However, this is not achievable in practice, due to small model movements during run conditions, and the two cameras always view the model from two different locations. The usual correction procedure for these effects involves use of several image registration points or markers on the model surface after PSP coating; the alignment of PSP images can be obtained based on rigid body dynamics by assuming a second- or third-order polynomial fit for the movements of these markers between wind-on and wind-off conditions. In the present experiments, all the PSP images have been transformed using a third-order polynomial fit available in the OMS software. It has been found[6] that such transformation procedures are adequate when the surface curvatures and the model displacements are small and there exist an adequate number of image registration points on the model, which are located ideally.[15,16] For the test conditions of the present study, the model deflection due to aerodynamic loads has been estimated to be less than 0.1 deg, which is quite small, and therefore the use of polynomial transformation seems appropriate. For all test cases in the present experiments, it was observed that the maximum image misalignment using 35 image registration points was typically around 5 pixels on the wing and 15 pixels on the fuselage. The larger misalignment observed on the fuselage is mainly due to use of a polynomial approach on the fuselage having a large curvature. Flat field correction of the CCDs, which is usually small,[17] has not been applied in the present case.

In order to carry out the PSP image analysis, we need to define an appropriate model temperature for each blowdown. In the present set of measurements, it was found that the total temperature drop was about 5–6°C during a typical blowdown duration of about 20 s. A

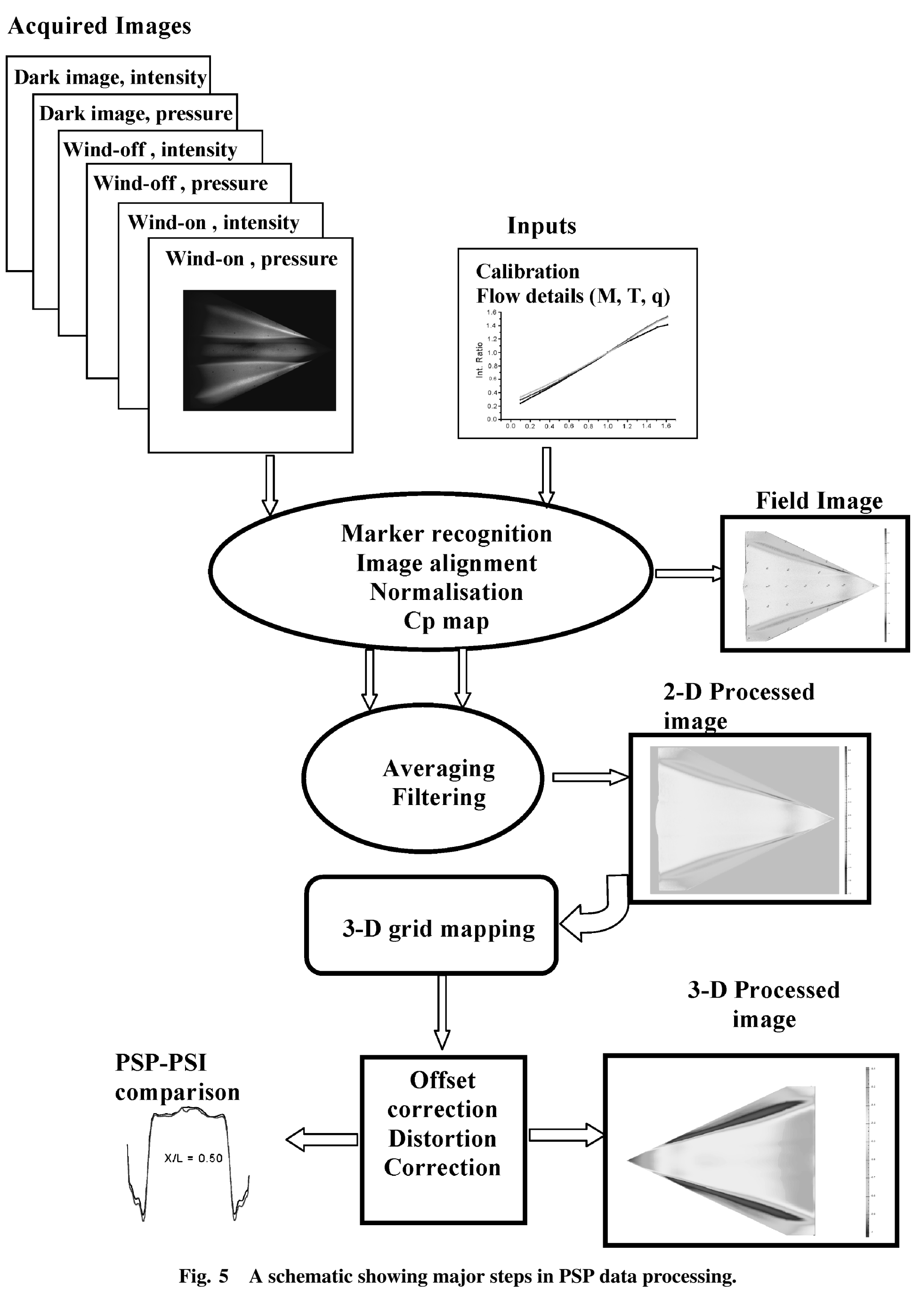


Fig. 5 A schematic showing major steps in PSP data processing.

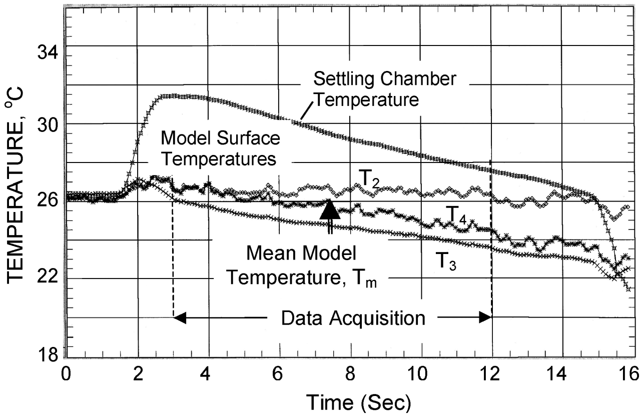


Fig. 6 Typical temperature variation in the settling chamber and model surface during a blowdown.

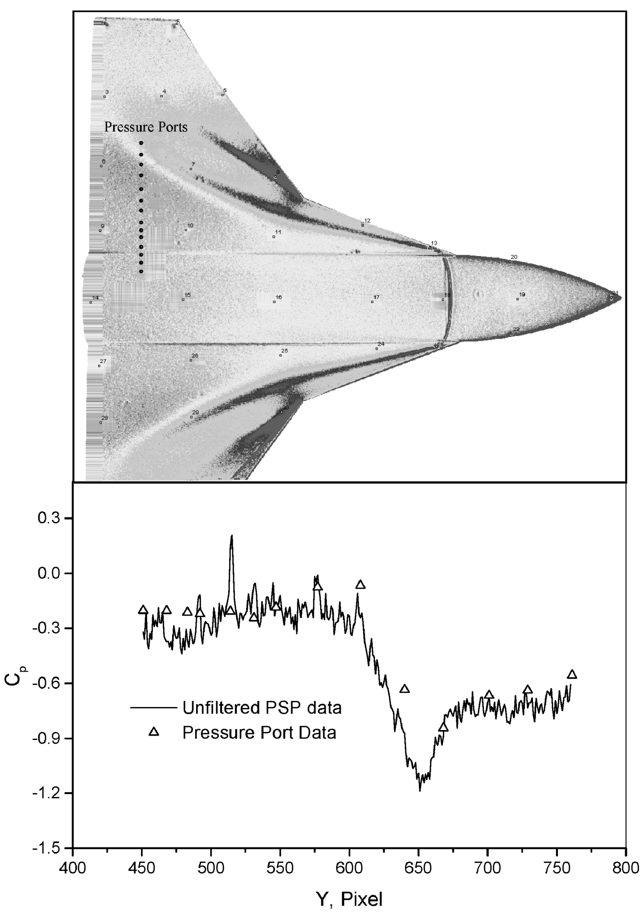


Fig. 7 Pressure map and comparison of PSP data on the wing–body model before filtering and grid mapping: $M = 0.8$, $\alpha = 10$ deg.

representative example of temperature history during PSP image acquisition is shown in Fig. 6. As may be observed, the drop in model temperature is about 2°C for the particular blowdown shown (although it was typically in the range of 2–3°C for other blowdowns) and the spatial variation of temperature over the model surface was typically 1.5°C (the thermocouple T_1 malfunctioned during the tests and therefore its output is not shown in Fig. 6).

The procedure employed for temperature correction and the assumptions made are as follows:

1) We define a mean temperature (T_m) of the model during the PSP acquisition, as shown in Fig. 6. T_m is the mean of the initial and final average temperatures, $[(T_1 + T_2 + T_3)/3]$, immediately before and just after the blowdown. The above approximation seems justified due to a small temperature drop of about 2–3°C.

2) The wind-off images immediately before and after the blowdowns were averaged, providing essentially a wind-off image at T_m. This procedure was adopted because it was very practical considering the small model temperature drop (about 2–3°C), and also, the temperature variation is nearly linear during a blowdown (Fig. 6).

3) PSP calibration at T_m is utilized for processing all images of a given blowdown.

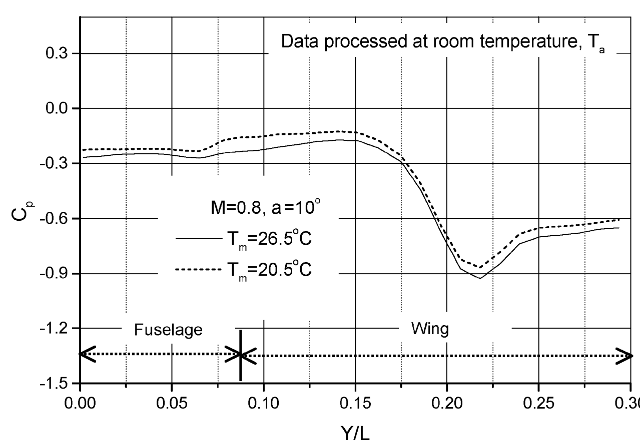
Results and Discussion

A summary of the major tunnel parameters and mean temperature of the model (inferred based on the methodology described above) for all the blowdowns conducted is presented in Table 1.

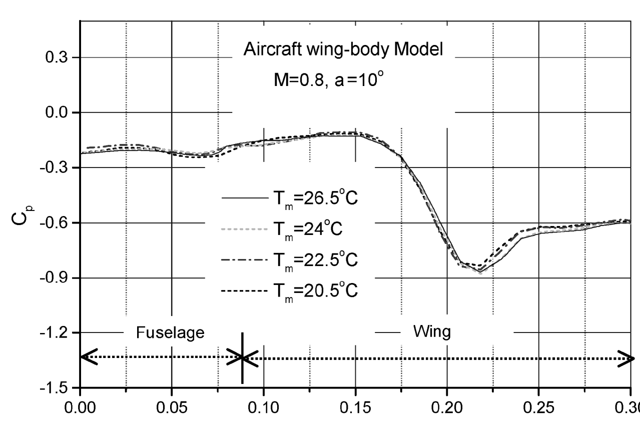
Table 1 Test parameters[a]

Run	Mach number	α, deg	T_m, °C
1	0.8	10	26.5
2	0.8	10	24.0
3	0.8	10	22.5
4	0.8	10	20.5
1	0.6	10	28.0
2	0.6	10	26.0
3	0.6	10	24.0
4	0.6	10	22.5
1	0.8	6	27.0
2	0.8	6	25.0
3	0.8	6	23.0
4	0.8	6	22.0
1	0.6	6	29.0
2	0.6	6	27.0
3	0.6	6	26.0
4	0.6	6	25.0

[a]The ambient temperature was about 28°C for most of the blowdowns.



a) Spanwise pressure distributions showing temperature effects



b) Spanwise pressure distribution: temperature-corrected PSP data

Fig. 8 Uncorrected and temperature-corrected PSP data.

It may be observed from Table 1 that the value of T_m for different blowdowns, for the same Mach number and model incidence, typically varies by about 5–6°C. Also, four blowdowns for each combination of M and α were carried out in order to generate temperature variation by about 5–6°C as mentioned.

It is a common practice that the processed PSP data is finally presented using an appropriate spatial filter. An example of an unfiltered PSP image (corrected for temperature) at $M = 0.8$ and $\alpha = 10$ deg is displayed in Fig. 7 along with a comparison with pressure port data. As may be expected, the PSP results show considerable noise and hence need to be filtered to make meaningful comparisons.

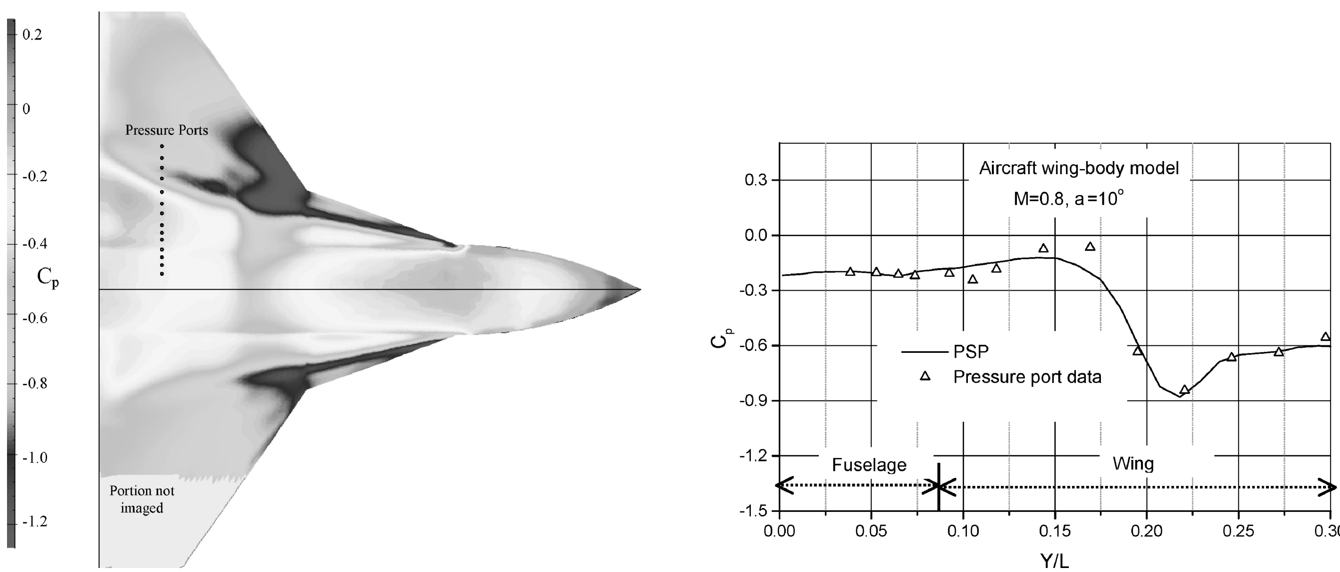
With an average image misalignment in the present work of about 10 pixels, we have used a 10 pixel × 10 pixel Gaussian filter to smooth PSP data, and the results are presented with these filtered images. In what follows, we first describe in detail the outcome of PSP data processing with the mean temperature hypothesis (described earlier) for the test case at $M = 0.8$ and $\alpha = 10$ deg. Following this, we present only the final results for the other three test conditions.

Temperature-Corrected PSP Data

The typical effect of model temperature on PSP data for the case of $M = 0.8$ and $\alpha = 10$ deg, with the data processed at an ambient temperature of 28°C, is shown in Fig. 8a for two specific blowdowns providing a maximum variation in the value of model surface temperature ($T_m = 26.5$ and 20.5°C). It may be observed that the maximum difference in C_p values for the above two cases is about 0.1 and the trend of the PSP curve is consistent with the sign of the temperature coefficient for the Optrod-B1 paint (+0.35%/°C).

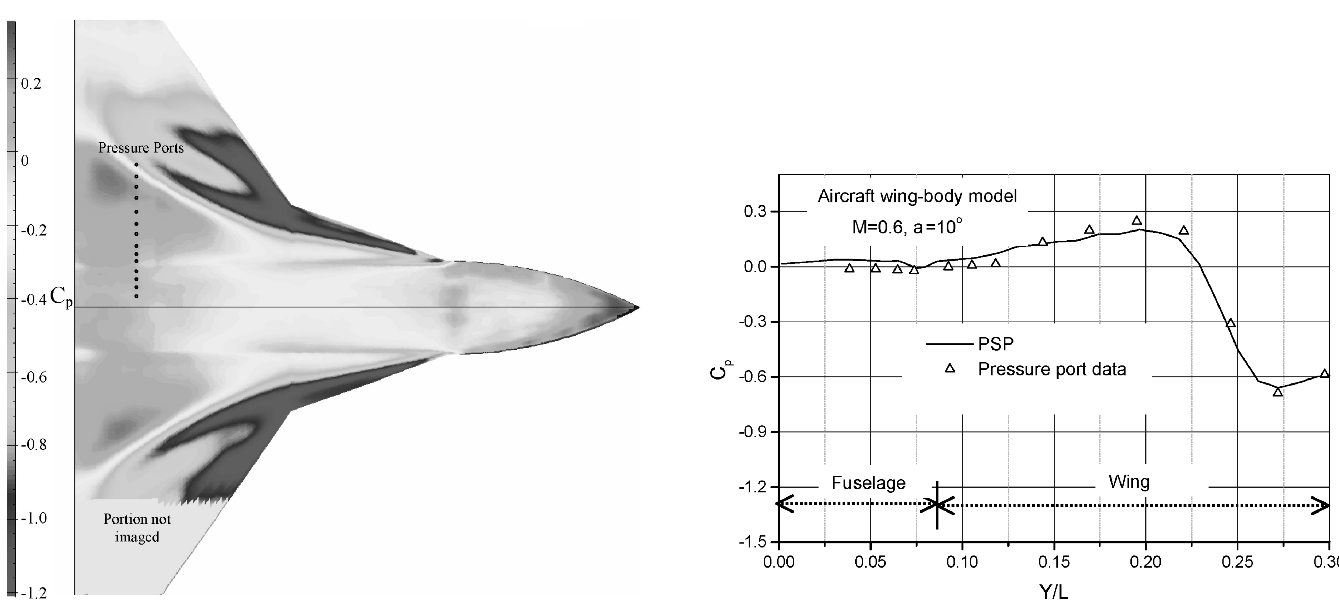
Figure 8b shows the PSP data at $M = 0.8$ and $\alpha = 10$ deg for all four blowdowns with the images processed using appropriate calibration factors at T_m (Table 1). As may be expected, the PSP data for the four blowdowns show a near collapse (with considerably reduced differences in C_p) without any dependence on T_m. The above results demonstrate the effectiveness of using mean model temperature for PSP data processing.

Temperature-corrected PSP data averaged for the four blowdowns for each M–α combinations are shown in Figs. 9–12. A comparison



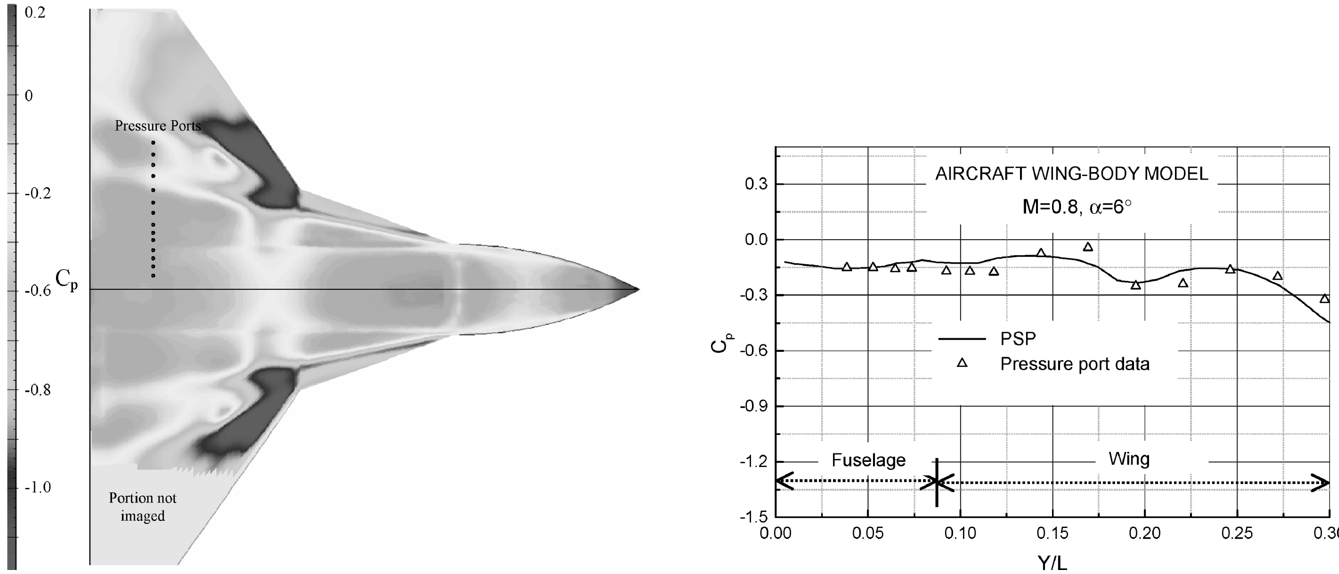
a) Lee-surface pressure map **b) Comparison of PSP data with pressure port data**

Fig. 9 Results on aircraft wing–body model at $M = 0.8$ and $\alpha = 10$ deg.



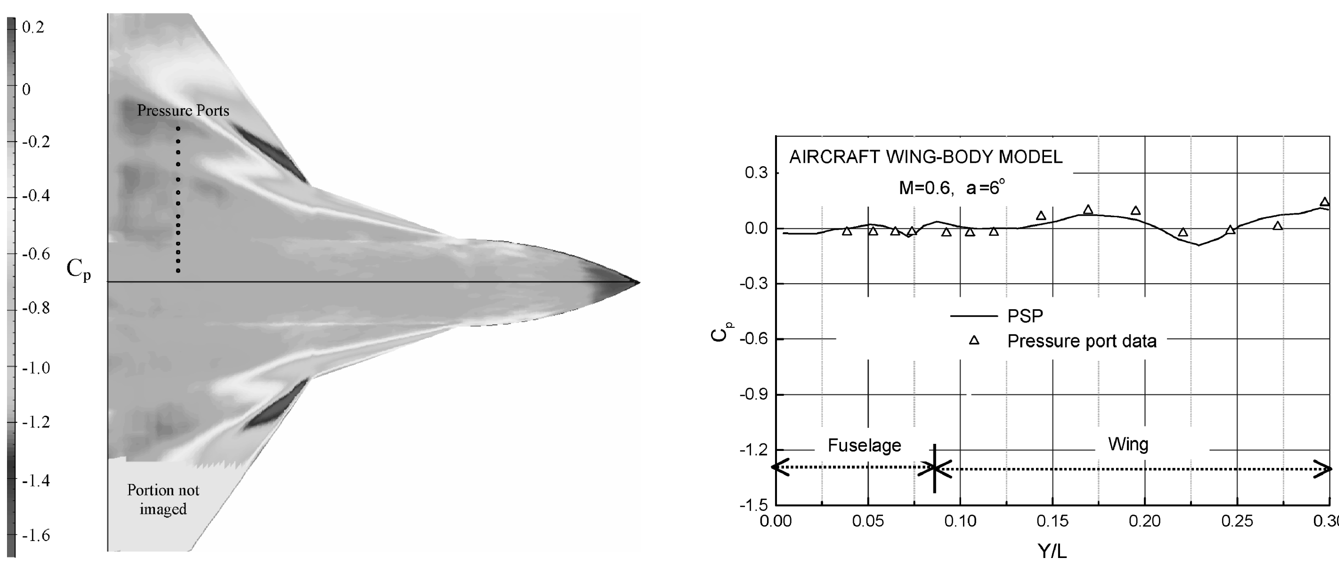
a) Lee-surface pressure map **b) Comparison of PSP data with pressure port data**

Fig. 10 Results on aircraft wing–body model at $M = 0.6$ and $\alpha = 10$ deg.



a) Lee-surface pressure map **b) Comparison of PSP data with pressure port data**

Fig. 11 Results on aircraft wing–body model at $M = 0.8$ and $\alpha = 6$ deg.



a) Lee-surface pressure map **b) Comparison of PSP data with pressure port data**

Fig. 12 Results on aircraft wing–body model at $M = 0.6$ and $\alpha = 6$ deg.

of results given in Fig. 7 and Fig. 9 shows clearly that filtering adopted here (10×10 pixels) has the effect of smoothing the suction peak (as expected), which is captured in the unfiltered PSP image.

The PSP pressure maps give a quantitative visualization capturing all the important features of the vortical flow development on the wing. At $M = 0.8$ and $\alpha = 10°$, some asymmetry in the vortex flow features is observed (Fig. 9a) in the vicinity of the first kink in the delta planform, which may be a result of shock–vortex interaction at this relatively high Mach number and α. The flow features display good symmetry at other conditions, as revealed in pressure images (Figs. 10–12). It may be observed that the comparison between the pressure port data and PSP for all four test cases on the aircraft model is generally good and the agreement in C_p is within ± 0.03 to 0.04 for most data, which translates to an average error of about 1.5 kPa. This degree of accuracy of PSP results obtained here may be judged to be about as good as those obtained at transonic speeds in wind tunnels elsewhere.[12,18]

Conclusions

An experimental study of PSP measurements on an aircraft model was undertaken in a blowdown wind tunnel at transonic speeds, primarily to provide a correction method for the PSP data due to drop in model temperature during a blowdown. The tests were made at Mach numbers of 0.6 and 0.8 and at model incidences of 6 and 10 deg. The aircraft model was coated with Optrod-B1 binary paint on the lee side of the wing, including the fuselage. The model was instrumented with four thermocouples on the model surface to monitor the surface temperature during a blowdown and 14 static pressure ports along the model span for comparison with PSP results. A correction method to account for temperature effects on PSP data based on the mean temperature of the model during a blowdown has been suggested and its usefulness demonstrated by comparison with conventional pressure port data. The accuracy of temperature-corrected PSP results is observed to be about as good as for those obtained at transonic speeds elsewhere.

Acknowledgments

This work was funded by the Aeronautics R&D Board of the Government of India. The authors express sincere thanks to Rolf H. Engler and Christian Klein (DLR Institute of Aerodynamics and Flow Technology, Goettingen, Germany) for initiating us into the technique of PSP measurement, for their advice on PSP system specifications, and for their contributions to the PSP commissioning tests in the NAL 1.2-m tunnel. Sincere thanks are due to L. Venkatakrishnan for his valuable comments and suggestions. Grateful thanks are due to S. P. J. Achar, all the members of the 1.2-m tunnel staff, G. Rajeev, Mahesh Kadam, and the NTAF Design and Drawing group for their valuable help in the test program.

References

[1]Sellers, M. E., "Application of Pressure Sensitive Paint for Determining Aerodynamic Loads on a Scale of the F-16C," AIAA Paper 2000-2528, June 2000.

[2]Engler, R. H., Klein, C., Merlo, E., and Amerom, P. V., "360° PSP Measurements in Transonic Flow," *Proceedings 16th International Congress on Instrumentation in Aerospace Simulation Facilities*, IEEE, Cleveland, 2001.

[3]Schairer, E. T., Mehta, R. D., and Olsen, M. E., "Effects of Pressure-Sensitive Paint on Experimentally Measured Wing Forces and Pressures," *AIAA Journal*, Vol. 40, No. 9, 2002, pp. 1830–1838.

[4]Crites, R. C., "Pressure Sensitive Paint Technique," *Measurement Techniques*, Lecture Series 1993-05, Von Karman Institute of Fluid Dynamics, Rhode Saint Genese, Belgium, 1993.

[5]Liu, T., Campbell, B. T., Burns, S. P., and Sullivan, J. P., "Temperature and Pressure Sensitive Luminescent Paints in Aerodynamics," *Applied Mechanics Reviews*, Vol. 50, No. 4, 1997, pp. 227–246.

[6]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.

[7]Liu, T., Guille, M., and Sullivan, J. P., "Accuracy of Pressure Sensitive Paint," AIAA Paper 99-3785, June–July 1999.

[8]Woodmansee, M. A., and Dutton, J. C., "Treating Temperature-Sensitivity Effects of Pressure Sensitive Paint Measurements," *Experiments in Fluids*, Vol. 24, No. 2, 1998, pp. 163–174.

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

[10]Mébarki, Y., and Le Sant, Y., "Pressure Sensitive Paint Evaluation on a Supercritical Wing at Cruise Speed," *Journal of Visualization*, Vol. 4, No. 4, 2001, pp. 313–322.

[11]Egami, Y., Iijima, Y., Amao, Y., Asai, K., Fuji, A., Teduka, N., and Kameda, M., "Quantitative Visualisation of the Leading-edge Vortices on a Delta Wing by Using Pressure Sensitive Paint," *Journal of Visualization*, Vol. 4, No. 2, 2001, pp. 139–150.

[12]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.

[13]Klein, C., Engler, R. H., Raju, C., Viswanath, P. R., and Achar, S. P. J., "PSP Measurements on a Wing–Body Model in the 1.2 m Trisonic Wind Tunnel," NAL Report NAL-SP-0110, Experimental Aerodynamics Division, National Aerospace Laboratories, Bangalore, Aug. 2001.

[14]Kline, S. J., and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Vol. 75, Jan. 1953, pp. 3–8.

[15]Venkatakrishnan, L., "Application of Resection on PSP Data Processing," NAL Report NAL-PD-3114, Experimental Aerodynamics Division, National Aerospace Laboratories, Bangalore, Nov. 2003.

[16]Liu, T., Cattafesta, L. N., and Radeztsky, R. H., "Photogrammetry Applied to Wind Tunnel Testing," *AIAA Journal*, Vol. 38, No. 6, 2000, pp. 964–971.

[17]Mendoza, D. R., "An Analysis of CCD Camera Noise and Its Effect on Pressure Sensitive Paint Instrumentation System Signal to Noise Ratio," ICIASF '97 IEEE, Pacific Grove, CA, 1997, pp. 22–29.

[18]Dowgwillo, R. M., Morris, M. J., Donovan, J. F., and Benne, M. E., "Pressure Sensitive Paint in Transonic Wind-Tunnel Testing of the F-15," *Journal of Aircraft*, Vol. 33, No. 1, 1996, pp. 109–116.