Pressure distributions on swept/unswept wings using pressure sensitive paint

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Abstract. Pressure sensitive paint (PSP) is an optical-based technique for full-field pressure measurements. A polymer-ceramic PSP, Ru(dpp), with a porous material is used and is applied onto a Mylar tape which affixed to the model surface of NACA 0012 and ONERA M6 wings. The PSP results agree with the data using conventional pressure measurements reasonably well.

1. Introduction

For surface pressure measurements, conventional pressure taps give poor spatial resolution. Peterson and Fitzgerald [1] conducted a pioneer work on the PSP. When the paint is illuminated by light, the intensity of emissions is inversely proportional to the amount of local oxygen or the surface pressure. Previous studies [2-5] showed that the PSP results are in good agreement with pressure plots that use conventional pressure measuring devices.

This study conducts PSP measurements for a NACA 0012 airfoil and an ONERA M6 wing, as shown in Figure 1, in a compressible flow. The full-field pressure contours are obtained and compared with those using conventional pressure-tap techniques. Measurement uncertainty is also addressed.
2. Experimental setup
The experiments were conducted in the transonic wind tunnel (blowdown type, as shown in Figure 2) at the Aerospace Science and Technology Research Center (TWT/ASTRC), National Cheng Kung University. Major components of the facility include compressors, air dryers, cooling water system, storage tanks and a tunnel. Dew point of high-pressure air through the air dryers is maintained at -40°C under normal operation conditions. Air storage volume for three storage tanks is up to 180 m³ at 5.15 MPa. The 600-mm² test section is 1500 mm long. In the present study, the test section was assembled with perforated top/bottom walls and solid side walls. The freestream Mach numbers $M$ were 0.77 for a NACA 0012 airfoil and 0.70 for an ONERA M6 wing, while the angle of attack $\alpha$ was 0° and 3°, respectively. For all the tests, stagnation pressure $p_o$ was 172±0.5 kPa (25 psi) and stagnation temperature $T_o$ was room temperature. The corresponding Reynolds number $\text{Re}_c$ was 3.4 x $10^6$ and 2.4 x $10^6$. The experimental data using pressure taps refers to the study by McDevitt and Okuno [6] for a NACA 0012 airfoil ($M = 0.75$, $\alpha = -0.02^\circ$, $\text{Re}_c = 4 \times 10^6$) and Schmitt and Charpin [7] for an ONERA M6 wing ($M = 0.69$, $\alpha = 3.06^\circ$, $Re = 11.7 \times 10^6$).
Fluorescent paints are sensitive to pressure or temperature, which is related to the oxygen quenching of a luminescent molecule. This study used a polymer-ceramic PSP with a porous material as the supporting. A silica gel (\( \text{SiO}_2 \)), a mean of particle size of 70 to 90 Å) and a RTV-118 were chosen as the porous particle and polymer, respectively. To mix these components (3g:7g), Toluene was used as a solvent. As a luminophore, the absorption and emission spectra of Ru(dpp) (purchased from ALFA Co.) were 441-467 nm and 597 nm, respectively. Ru(dpp) was dissolved in Isopropyl alcohol (IPA) (1mg:1ml) and sprayed onto a Mylar tape which affixed to the model surface for mean pressure measurements. For temperature sensitive paint (TSP), UNT-400 (purchased from ISSI Co.) was used. The respective absorption and emission spectra were 460 nm and 500-720 nm. The response time was approximately 0.75 s.

Illumination came from Revox SLG-55 light sources with a short-pass filter (550 nm). A charge coupled device (CCD) camera (Pco. Pixelfly, 14-bit) with a long-pass (600 nm) filter was used at the frame rate of 20 Hz. Calibration was carried out in a vacuum chamber under reference pressures, as shown in Figure 3. A Stern-Volmer plot with four repeated tests is shown in Figure 4, in which \( \frac{I_{\text{ref}}}{I} = 0.331 + 0.653 \frac{p}{p_{\text{ref}}} \), where \( I_{\text{ref}} \) and \( p_{\text{ref}} \) are emission intensity and pressure at a reference condition, respectively. The wind-on images were acquired during the test and the wind-off reference image was acquired after the test. The data reduction uses prior calibration data and in-situ calibration, as shown in Figure 5. Note that the pressure and temperature sensitivities for Ru(dpp) are 0.64%/kPa and 1.5%/°C, while the values for TSP are 0%/kPa and 2.7-2.1%/°C.

![Figure 3. Setup for PSP calibration](image-url)
3. Results and discussion
For a NACA 0012 airfoil at $M = 0.77$ and $\alpha = 0^\circ$, the PSP/TSP results are shown in Figure 6. The flow accelerates near the front edge and the value of $C_p$ reaches the minimum at $x/L \approx 0.2$, following the compression toward the trailing edge. The surface temperature of the model using TSP varies up to 3 K, i.e. the minimal value near the front edge and the maximum value near the trailing edge. The
temperature offset is considered to be negligible. The data by McDevitt and Okuno [6] is used for comparison, as shown in Figure 7. The PSP follows the relative changes in pressure accurately. However, the relative error is approximately 25% at \(x/L = 0.1\).

For an ONERA M6 wing at \(M = 0.70\) and \(\alpha = 5^\circ\), the PSP and TSP results are shown in Figures 8 and 9. The flow decelerates from the leading edge to the trailing edge. For this swept wing, the 3-D effect is evident. The value of \(C_p\) near the front edge decreases when there is a decrease in the value of \(y/b\). At \(y/b = 0.65, 0.8\) and \(0.90\), pressure comparison between PSP and reference data [7] is shown in Figures 10-12. Note that the raw curve represents data processing using prior calibration only. The corrected curve corresponds to in-situ calibration. Deviation between PSP and pressure tapping measurements is within 5%. The PSP follows the relative changes in pressure accurately, but not near the leading edge. This is considered due the setup of the light source, i.e. the inclination angle between light source and model surface.

Figure 6. Surface pressure pattern on a NACA 0012 airfoil (M = 0.77)

Figure 7. Pressure comparison between PSP and reference data for a NACA 0012 airfoil
Figure 8. Surface pressure pattern on an ONERA M6 wing (M = 0.70)

Figure 9. Surface temperature pattern on an ONERA M6 wing (M = 0.70)

Figure 10. Pressure comparison between PSP and reference data for an ONERA M6 wing; y/b = 0.65
Figure 11. Pressure comparison between PSP and reference data for an ONERA M6 wing; \(y/b = 0.80\)

Figure 12. Pressure comparison between PSP and reference data for an ONERA M6 wing; \(y/b = 0.90\)

4. Conclusions
This study applies the PSP to measure surface pressure distributions for swept/unswept wings in a transonic wind tunnel. The TSP is also used to verify the temperature offset. The results demonstrate the PSP can follow the relative changes in pressure accurately, but not near the leading edge. Deviation between PSP and pressure tapping measurements is within 5%. However, the effect of the setup of light source should be taken into account to address the relative error.

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