Binary Pressure-Sensitive Paint

It is well documented in the literature that pressure sensitive paints exhibit undesirable sensitivity to variations in temperature and illumination. In fact, these variations in temperature and illumination are identified as the major sources of error in pressure sensitive paint measurements [1]. Several techniques for minimizing errors due to variations in temperature and illumination have been demonstrated, among the most promising is the concept of using a reference luminophor that simultaneously compensates for illumination and temperature. This concept is the basis of the Binary pressure sensitive paint developed by ISSI.

Compensation for Variations in Illumination

The luminescent intensity F, of a temperature- or pressure-sensitive paint as a function of pressure (P), temperature (T), luminophor concentration (N), and illumination (I) can be represented as

$$F = f(P,T,N,I) \quad . \qquad \text{Equation 1}$$

The common approach to eliminating variations in illumination, as well as variations in luminophor concentration or paint layer thickness, involves taking the ratio of a ***wind off*** image to that of a ***wind on*** image. This approach however assumes that the illumination at any point on the model surface is constant. The assumption of constant illumination is easily violated by slight variations in illumination intensity from the lamps, or more commonly, by slight movement or deformation of the model within the illumination field due to aerodynamic loads. The errors that result from these slight variations in illumination are more pronounced at low speeds where small changes in pressure (less than 1 psi) yield small changes in pressure sensitive paint luminescence (less than 1%). Therefore small variations in illumination significantly degrade the quality of the pressure data in low speeds.

One means of dealing with this issue is to employ a reference luminophor. The goal is to use the luminescence of the reference probe (*R*) to correct for variations in the luminescence of the signal probe (*S*, the pressure sensitive probe) that are caused by variations in paint illumination. This is accomplished by taking a ratio of the luminescence of the signal probe,

$$F_S = f_S(P,T,N_S,I) \qquad \text{Equation 2}$$

to the luminescence of the reference probe,

$$F_R = f_R(P,T,N_R,I) \, . \qquad \text{Equation 3}$$

Assuming that both the reference and signal probes response is linearly proportional to the local illumination and luminophor number density the resulting function r is

$$r(P,T) = \frac{F_S(P,T)\,N_S * I}{F_R(P,T)\,N_R * I} = \frac{F_S(P,T)\,N_S}{F_R(P,T)\,N_R} \, . \qquad \text{Equation 4}$$

The dependence of r(P,T) on illumination has been removed, however the system is still a function of temperature, pressure, and relative luminophor concentration. Theoretically, the paint components are homogeneous and the ratio of signal probe to reference probe (N_S/N_R) is constant, experience has shown that this is not the case. An example of this non-uniform probe deposition for a binary paint is shown in Figure 2. To remove the variations in the relative number density of the two probes, a ***wind on*** and ***wind off*** ratio (a ratio of ratios) is used.

$$L(P,T) = \frac{r_0(P_0,T_0)\,{}^{N_S}\!\!\diagup\!{}_{N_R}}{r(P,T)\,{}^{N_S}\!\!\diagup\!{}_{N_R}} = \frac{r_0(P_0,T_0)}{r(P,T)}. \qquad \text{Equation 5}$$

The effectivness of this approach is demonstrated in Figure 3. Here, the data presented in Figure 2 has been divided by a second set of ratioed data. The noise caused by the non-uniform probe concentration has been significantly reduced and the system response is now a function of pressure and temperature only.

At first it may appear that little has been gained by the system described in Equation 5. The experimentalist is still required to acquire a ***wind off*** image, in fact two images are now required at each condition rather than one. To demonstrate the power of the binary paint technique the user must also incorporate the process of image alignment or image mapping. The data reduction process described by Equation 5 is carried out in two steps. First the ratio of the signal probe to the reference probe is computed for both the ***wind off*** and ***wind on*** conditions. This ratio eliminates illumination from the system. Now to remove probe concentration, the ***wind on*** ratio image is mapped onto the ***wind off*** ratio image and the ratio of ratio is computed to remove the effects of probe concentration. Note that since all ***wind on*** images can be mapped back onto a single ***wind off*** image only a single ***wind off*** image is required. Used in this mode, the binary paint effectively eliminates half of the model configurations because only a single wind off condition is necessary. This represents a significant improvement in tunnel productivity. At the same time the errors in the pressure measurements caused by illumination have also been minimized therefore, the binary paint system provides several significant improvements over a traditional pressure-sensitive paint system.

Selection of the reference probe is by no means trivial. The reference probe must be excited by the same illumination source that is used to excite the signal probe and the luminescence of the reference probe must be spectrally separated from the luminescence of the signal probe. Finally to maximize the pressure sensitivity of the system, the reference probe should exhibit as little sensitivity to pressure as possible.

Compensation for Temperature

With illumination removed from equation 5 the goal becomes minimizing the sensitivity of the system to temperature. The approach utilized involves allowing the reference probe, which is eliminating sensitivity to illumination, to compensate for the temperature sensitivity as well. While any degree of temperature-sensitivity in the reference probe will yield a reduction in the temperature-sensitivty of the final pressure-sensitive paint calibration, effective temperature compensation over a wide range of pressures is most easily attained by using an ideal paint.

All pressure-sensitive paints exhibit some temperature-sensitivity. Temperature-sensitivity of pressure-sensitive paint is caused by several physical processes such as temperature-dependent oxygen permeability in the paint binder and thermal quenching of the luminescent probe. For most pressure-sensitive paints the temperature-sensitivity of the paint is a function of pressure and the pressure-sensitivity of the paint is a function of temperature. This coupling of temperature and pressure sensitivity was recognized as an undesirable feature by Puklin, Ponomarev, and Gouterman [2] who outlined the concept of the ideal paint. In an ideal paint the pressure dependence is not a function of temperature and the temperature dependence is not a function of pressure.

Eliminating sensitivity to temperature sensitivity is accomplished by adding two constraints to the selection criteria already outlined for a the binary paint. 1) The combination of the signal probe and paint binder must form an ideal paint. 2) the temperature sensitivity of the reference probe must match the temperature sensitivity of the ideal paint. ISSI has developed a binary paint based on the PtTFPP/FIB pressure-sensitive paint. PtTFPP/FIB is an ideal paint as defined above and therefore compensation of the temperature-sensitivity over a wide range of pressures is possible. The calibration process for this paint is described below.

Calibration of Binary Pressure-Sensitive Paint

The equipment and procedure for calibration of a binary pressure-sensitive paint is similar to that used for single component paint systems. Once again, the ISSI pressure-sensitive paint calibration chamber (Figure 4) is used to control the temperature and pressures to which the paint is exposed. A 4 cm by 4 cm aluminum coupon is painted with the binary pressure sensitive paint and this coupon is seated onto a Peltier thermo-electric cooler and mounted inside the calibration chamber. The pressure inside the calibration chamber is controlled using a Ruska pressure controller while the temperature of the sample is controlled using an Omega temperature controller. The sample is illuminated using an ISSI LM-2 Lamp, this lamp uses an array of 76 blue LED’s to produce excitation at 405 ± 10 nm. The sample is imaged through a filter wheel onto a PCO Series 1600 CCD camera. The filter wheel contains a 645-nm long pass filter for the signal probe and a 550 ± 40-nm band-pass filter for the reference probe. The calibration is begun by recording the luminescence of the signal (F_S) and reference (F_R) probes at 298 K and 14.696 psia, this serves as the reference condition. The temperature and pressure within the chamber are then varied over a range of temperatures and pressures. The luminescence from each probe is recorded at each condition and the ratio of ratios as defined in equation 5 is computed and plotted versus pressure. A calibrations for binary this binary paint (BF405) is shown in Figure 5, this paint exhibits good pressure sensitivity (4.5% per psi) with very little temperature sensitivity (less than 0.03 % per K)

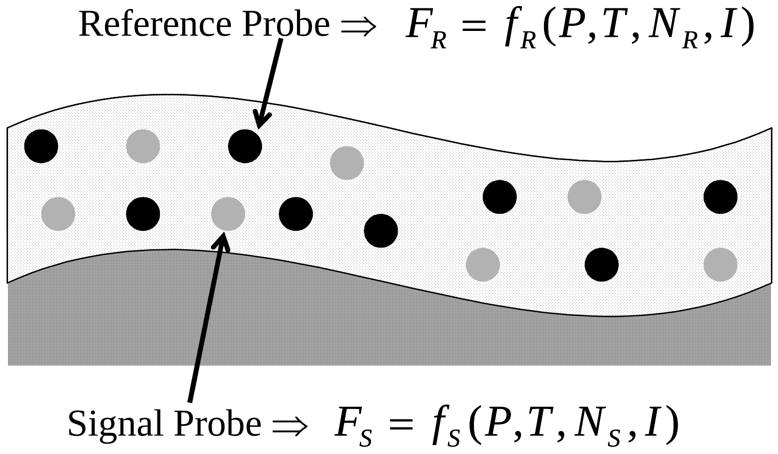

Figure 1 Binary pressure-sensitive paint showing signal and reference probes.

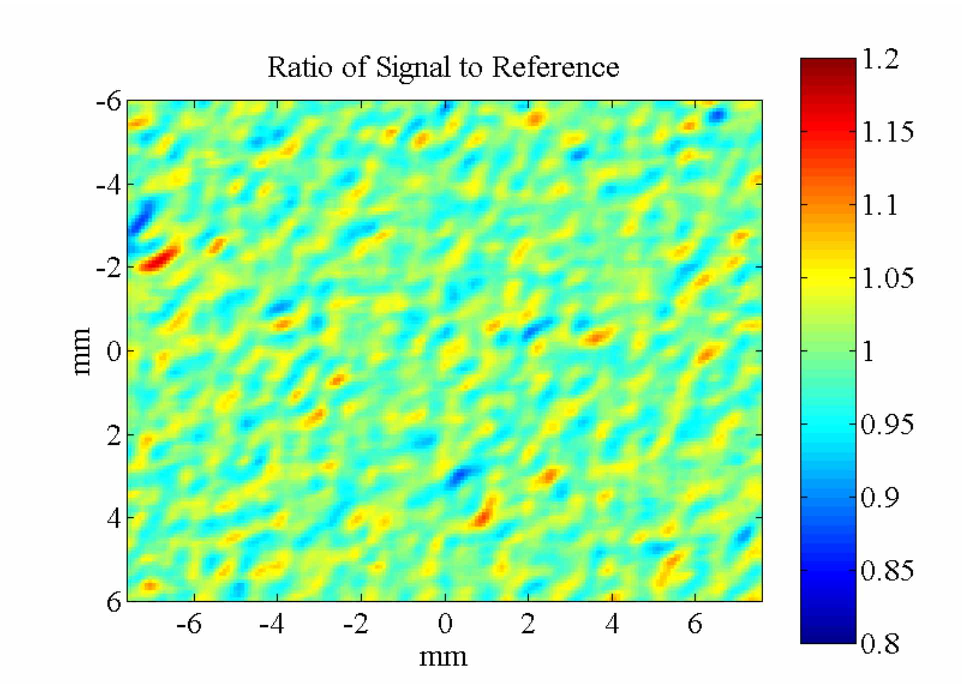

Figure 2 Ratio of signal probe to reference probe for a binary pressure-sensitive paint as described by Equation 4. The spread in the ratio is the result of the non-uniform deposition of the signal and reference probes in the binder. The standard deviation is ~ 3%.

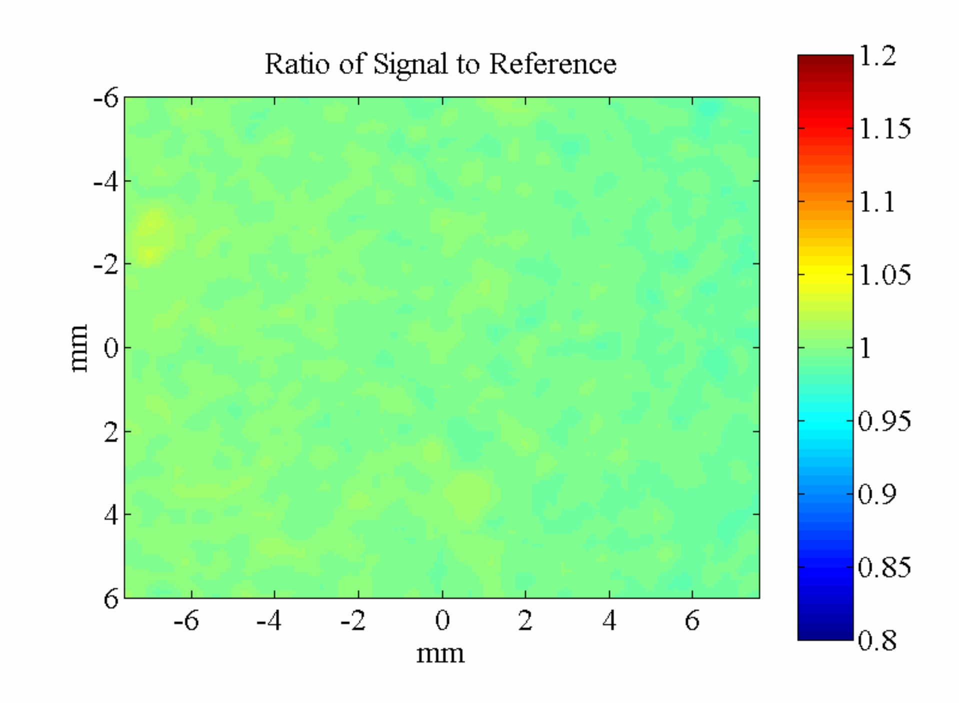

Figure 3 Ratio of ratio for the binary pressure-sensitive paint shown in Figure 2 as described by Equation 5. Note that the spread in the ratio has been reduced substantially by this process even though the shot noise should increase due to the use of 4 images. The standard deviation is ~ 0.5%.

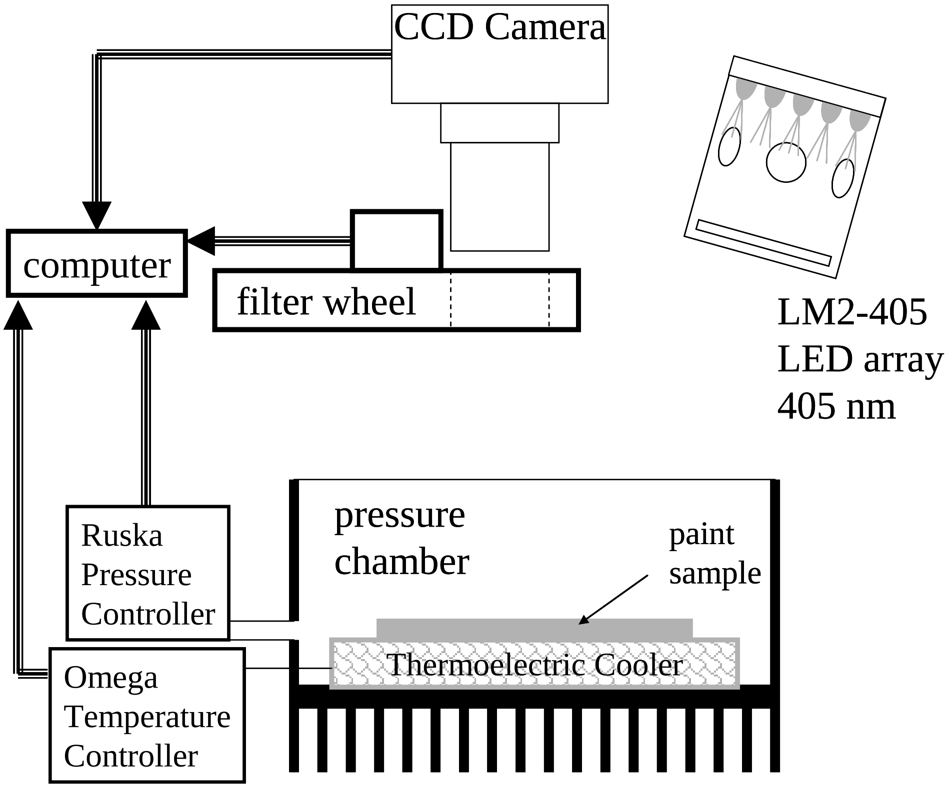

Figure 4 Pressure-Sensitive Paint calibration system.

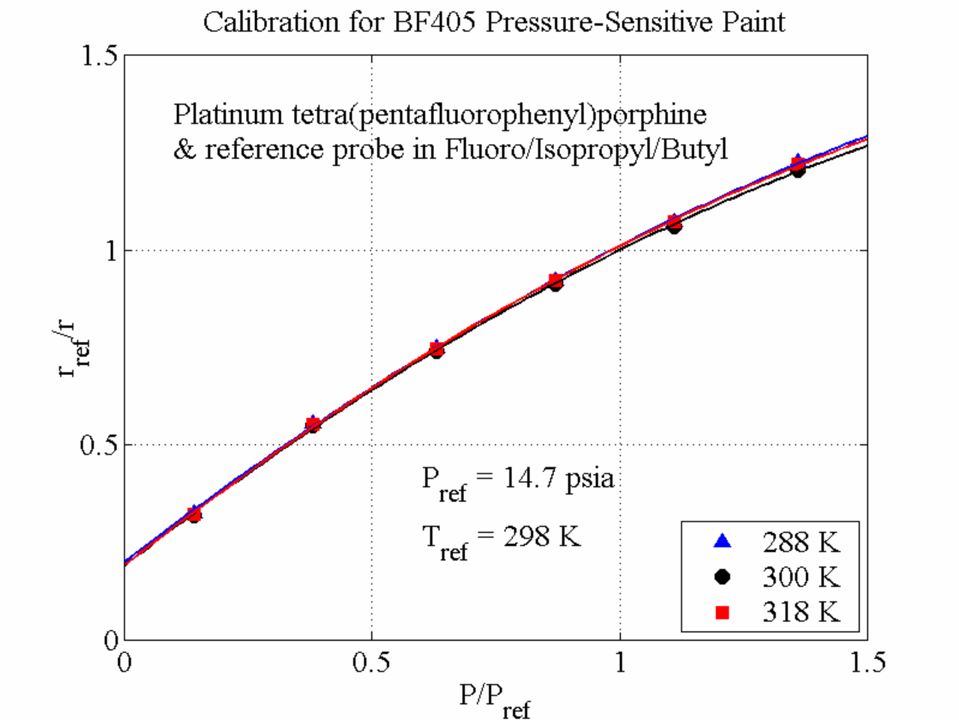

Figure 5 ISSI Binary FIB. Exhibits good pressure sensitivity (4.5% per psi) and low temperature sensitivity. (0.03% per K).

Contact Information

Innovative Scientific Solutions, Inc.
2766 Indian Ripple Road Dayton OH 45440
Phone: (937) 429-4980 x107
Email: sales@innssi.com
Web: www.innssi.com

References

[1] T. Liu.,M. Guille, J.P. Sullivan, "Accuracy of Pressure Sensitive Paint", AIAA Journal, vol. 39, n 1, pp. 103-112, (2001)

[2] Gouin, S., Gouterman, M., "Ideality of Pressure-Sensitive Paint. I. Platinum Tetra(pentafluorophenyl) porphine in Fluoroacrylic Polymer", Journal of Applied Polymer Science, Vol. 77, pp. 2795 – 2804, (2000)