Comparison of Radiometric and Lifetime based Pressure-Sensitive Paints for Low Speed Pressure Measurements

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Over the past ten years the technology of Pressure-Sensitive paint has been deployed in several high speed wind tunnels as a standard instrument. Efforts to extend the use of this technology into the low speed regime have proven difficult. While several successful tests at low speed have been demonstrated, these results generally required very careful experimental procedures. In an effort to produce a robust low speed Pressure-Sensitive paint system, ISSI has instigated several approaches for minimizing the uncertainties associated with Pressure-Sensitive paint measurements. The two most promising approaches for general applications are the Radiometric Binary and Dual Lifetime systems. These techniques have been applied for measurements in several low speed experiments and the results are presented here. These results indicate that practical measurements with a resolution of one one-hundredth of a psi are possible; however care must be taken in the design of the experiment to achieve this resolution.

I. Introduction

PRESSURE-SENSITIVE paint (PSP) techniques have been applied extensively to the study of high-speed flows. Efforts at NASA, Boeing, AEDC, ONERA, DLR, and JAXA are just a few examples of applications of PSP techniques to large, high-speed wind-tunnel facilities. While PSP has proven to be an effective tool in high-speed flows, deployment of this technology to low-speed wind tunnels has been hindered by several sources of uncertainty1 which are inherent in the PSP technique. Among these uncertainties are errors due to model displacement and deformation, instability of the illumination source, photo-degradation and sedimentation of the painted surface, and non-uniform temperatures on the model surface. While it has been shown that these errors can be minimized through careful experimental procedures, practical deployment of PSP to low speed wind tunnels will require a robust solution to these sources of error. Two techniques that have demonstrated potential as a solution to these errors are Binary and Lifetime PSP techniques. In this paper we will evaluate the advantages and disadvantages of each technique and compare the experimental results from each technique from several models in a low speed wind tunnel.

A. Pressure-Sensitive Paint

A typical pressure sensitive paint is composed of two parts, an oxygen-sensitive fluorescent molecule, and an oxygen permeable binder. The pressure sensitive paint method is based on the sensitivity of certain luminescent molecules to the presence of oxygen. When a luminescent molecule absorbs a photon, it transitions to an excited singlet energy state. The molecule then typically recovers to the ground state by the emission of a photon of a longer wavelength. In some materials oxygen can interact with the molecule such that the transition to the ground state is non-radiative, this process is known as oxygen quenching. The rate at which these two processes compete is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus giving off a lower intensity of light.

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Image based pressure measurements using PSP are accomplished by coating the model surface with the paint and illuminating the surface with light of the appropriate wavelength to excite the luminescent molecule. The surface is imaged through a long-pass filter to separate the luminescent signal from the excitation light and the luminescent signal distribution is recorded. A schematic of the system is shown in Figure 1. Unfortunately, the luminescent signal from the paint is not only a function of pressure. The luminescence varies with illumination intensity, probe concentration, paint layer thickness, and detector sensitivity. These spatial variations result in a non-uniform luminescent signal from the painted surface. The spatial variations are eliminated by taking the ratio of the luminescent intensity of the paint at an unknown test condition, \( I \), with the luminescent intensity of the paint at a known reference condition, \( I_o \). Using this \textit{wind-on wind-off} ratio, the response of the system can be modeled using a modification of the Stern-Volmer equation.

\[
\frac{I_o}{I} = A(T) + B(T) \frac{P}{P_o}
\]  

\( (1) \)

**B. Sources of Error in Pressure-Sensitive Paint Measurements**

While there are several approaches to acquiring PSP data, each of these approaches suffer from the same sources of error. The sources of uncertainty for PSP measurements have been investigated and modeled by Liu. These error sources include temperature, illumination, model displacement/deformation, sedimentation, photo-degradation, stray light, and camera shot noise. As described above PSP is an intensity-based approach, this is true for both radiometric and lifetime systems. The sensitivity of the paints to pressure is relatively constant as a function of pressure. At lower speeds the total dynamic range of pressures encountered is small and therefore the total change in intensity to be detected is also small. While the sources of error mentioned by Liu are present in both high and low-speed PSP experiments they represent a more significant percentage of the total dynamic range in low speed tests. For this reason care must be taken to evaluate and eliminate these sources of error for low speed test.

**II. Approaches to Pressure-Sensitive Paint Measurements**

While the physical mechanism of oxygen quenching is the basis of all PSP techniques, there are several approaches used to detect this process and exploit it for measurements of absolute pressure. These are generally classified as Radiometric or Lifetime techniques. Radiometric measurements attempt to detect the absolute intensity from the paint while Lifetime techniques use a variety of approaches to determine the luminescent lifetime of the active molecule. A further distinction between approaches is related to the number of active probes in the paint, i.e. single channel or binary paints. Traditional PSP systems, both Radiometric and Lifetime, utilized paints that employ a single active probe. Later researches introduced a second active probe to compensate for...
various sources of uncertainty such as model displacement or temperature. These paints are known as binary paints and the resulting systems are known as Radiometric Binary or Dual Lifetime systems. Each of these systems will be described in the following.

C. Radiometric Pressure-Sensitive paint

A traditional PSP system is configured as shown in Figure 1 and operates as described in section A. Two images are acquired, a wind-off and a wind-on image. To minimize the influence of ambient lighting a background image is also acquired and subtracted from these images. The ratio of these images is then converted to pressure using an a-priori or in-situ calibration. For these traditional PSP systems, displacement or deformation of the model between the wind-off and wind-on images is a major issue. Even a slight displacement of the model can modify the illumination field and thus the recovered pressure field is more representative of the illumination field than of the pressure field. A second source of error is modification of the temperature of the painted surface between the acquisition of the wind-off and wind-on images.

Errors caused by model deformation/displacement and temperature can be minimized by carefully designing the experiment. The use of rigidly mounted models constructed of metal is ideal. This prevents movement or warping of the model due to aerodynamic loads and provides an isothermal surface for the paint. Attention should be paid to data acquisition and tunnel/experiment operation procedures as well. Wind-on and wind-off images should be acquired at as close a time interval as possible to minimize changes in illumination intensity and model surface temperature. This generally means that for each condition, wind-on images should be acquired only after the experiment has reached some level of thermal equilibrium and wind-off images should be acquired immediately following the wind-on images. In a closed circuit tunnel, this process can take several hours. The final issue is shot noise. To minimize the shot noise from the camera, it is desirable to average many images. Acquiring these images however, takes time and other experimental parameters may drift during this time. The number of images that may be averaged, and thus the ultimate resolution of the data, will vary with each experiment.

D. Binary Pressure-Sensitive Paint

One means of dealing with several of the common sources of error such as illumination and temperature is to employ a reference probe; several groups have successfully demonstrated this approach.\(^2\)\(^3\) The first step is to add a spectrally distinct reference probe to a standard PSP. The luminescence of the reference probe is used to correct for variations in the luminescence of the signal probe (the pressure sensor) that are due to variations in illumination. This is accomplished by taking a ratio of the luminescence of the signal probe to the luminescence of the reference probe. Assuming that both the signal and reference probes response is linearly proportional to the local illumination and probe number density the resulting function is

\[
R(P, T, n_S, n_R) = \frac{F_S(P, T) n_S I}{F_R(P, T) n_R I}
\]

The dependence of R on illumination has been removed; however R is still a function of temperature, pressure, and the concentration of each probe. If the distributions of the signal and reference probes are identical, the dependence on probe concentration is removed. This condition however, is difficult to achieve. An example of the probe distribution in a Binary paint is shown in Figure 2. Here we see a variation of 2% to 3% in the concentration of the signal and reference probes. To eliminate the effects of probe concentration, the standard wind on and wind off ratio (a ratio of ratios) is applied.
The system response \( S \) is now a function of pressure and temperature only. 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. The reference probe must be compatible with the solvents and binders that are used for the signal probe. Finally to maximize the pressure sensitivity of the system, the reference probe should exhibit as little sensitivity to pressure as possible.

With illumination removed from equation 3 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. A binary PSP composed of PtTFPP/FIB and a selected reference probe has been used to produce a PSP with low temperature sensitivity. The calibration of this paint is shown in Figure 3. The temperature sensitivity of ISSI Binary FIB is less than 0.05% per degree K over a range of temperatures from 5 – 45 C and pressures from 1 – 20 psia.

The above description may lead one to the conclusion that experimental setup is of no concern when using Binary PSP, this would not be correct. While errors due to model deformation/displacement and temperature may be minimized by the use of a Binary paint, several other sources of error are introduced. The first issue is camera shot noise, the data is now the result of four images rather than two and therefore the camera shot noise is doubled. A second issue is image alignment. Binary data can be acquired using two cameras, one for the signal channel and the other for the reference channel. The images are aligned, the ratio calculated according to equation 3. Errors associated with the alignment of the images can become the major source of error for low speed experiments. The preferred mode of operation is to use a single camera and a filter switch. All images are acquired through a single camera and lens, only the filter is changed, this process minimizes image alignment errors.

Among the most significant advantages of Binary paint systems is their ability to compensate for small changes in the illumination field. In many cases it is simply not possible to eliminate variations in illumination caused by relative movement between the model and the illumination source. This is common for flexible models such as those constructed of plastic/stereo-lithography materials or any model mounted on a force balance. Another significant advantage for a temperature compensating binary paint is that the insensitivity to temperature allows the acquisition of more images and thus the associated reduction in shot noise. While Binary paint systems can be effective for compensating for several sources of error, they should not be treated as a substitute for a well designed experiment.

E. Lifetime Pressure-Sensitive Paint

Approaches to measuring luminescent lifetimes for PSP have included phase-sensitive detection\(^4\) and multi-gate integration\(^6\) techniques. In each case all data are acquired at the wind-on condition, and this minimizes or eliminates illumination as a source of error as the displacement/deformation of the model between the wind-off and wind-on images is eliminated. A schematic of the two-gate lifetime approach is shown in Figure 4. The paint is excited to fluoresce using a short illumination pulse. Data are acquired in two distinct windows, in this case the first of these windows occurs during the illumination pulse and the second is centered on the decay of the fluorescence. The ratio of the integrated signal from the two gates is computed and the resulting signal is plotted versus pressure. The position and width of the gates is selected to maximize the system's sensitivity to pressure while maintaining a favorable signal to noise ratio.
Among the advantages of the lifetime approach is the elimination or minimization of illumination errors. Errors due to temperature are still a source of uncertainty in lifetime-based PSP measurements as is shown by a calibration of UniFIB using the two-gate approach in Figure 5. As one might expect, results obtained at low speeds using lifetime-based systems have been mixed. Errors due to model deformation/displacement should be minimal however; temperature errors could still be an issue.

One interesting feature of low speed lifetime-based experiments is the presence of wind-off noise. Theoretically, the lifetime of the paint at a uniform pressure and temperature should be constant at each point on the surface. It has been shown by several researchers that this is not the case. One explanation for this wind-off noise, in the case of PtTFPP based paints, is the presence of a second distinct probe. The process of producing PtTFPP involves a reaction between Pt and TFPP that can not be driven to completion. It has been noted that while the excitation and emission spectra of PtTFPP and TFPP are very similar, their luminescent lifetime are not. PtTFPP has a $\tau_0$ of about 100-µs while TFPP has a $\tau_0$ of less than 10-ns. This means that while the PtTFPP signal will appear in both gate 1 and gate 2, the TFPP will only be seen in gate 1. Much like a Binary paint, this would not be an issue if the two probes distributed themselves uniformly in the paint layer. This theory was tested by producing a UniFIB paint sample with TFPP added. The results indicate that while chemically similar, PtTFPP and TFPP do not distribute themselves uniformly as they come out of solution. In fact the result is similar to that shown in Figure 1, the variation in probe concentration can be as large at 10% and the rms is about 2%.

F. Dual Lifetime Pressure-Sensitive Paint

One means of compensating for the temperature sensitivity of the lifetime-based paints is to add a reference probe with a distinctly different lifetime. The data from this two lifetime paint can be acquired and processed in several ways. One possibility is to acquire data in four gates, thus creating two distinct lifetime measurements, and use the temperature measurement to compensate for temperature sensitivity in the pressure measurement. Another approach is to simply treat the system as a two-gate lifetime system. Temperature compensation, similar to that reported for Radiometric Binary paints, is achieved by adding a short lived probe with the correct temperature sensitivity that is manifest in the first gate. Essentially, this paint would operate as a Radiometric Binary paint but the probes would be isolated by time gates rather than spectral filters. A schematic of the Dual-Lifetime process is shown in Figure 6.

The data acquisition and data reduction process for the Dual-Lifetime paint is very similar to that of a Radiometric Binary paint, as are the sources of error. The issue of uniform distribution of the probes is again resolved using a wind-off ratio as described in equation 3. Sources of error are also very similar to those encountered with a radiometric Binary paint. As one might expect, the data obtained with this system is very similar to that obtained using a Radiometric Binary system.

III. Results

Several experiments have been performed using these PSP systems. The results for these experiments are reported here along with some...
discussion of the performance of these systems.

G. Impinging Jet

One of the most basic experimental setups encountered in PSP is the impinging jet. This experimental setup provides a small and easily controlled pressure environment to evaluate PSP systems. While conceptually simple, the impinging jet can provide a complex flow with both temperature and pressure gradients that can prove challenging for a PSP system. The experimental setup used here includes a compressed air supply fed through a regulator and into an 18-inch long by 4-inch diameter plenum. The plenum pressure is monitored using a Dwyer model 478 pressure transducer and the temperature is monitored using a type T thermocouple. The nozzle has rounded inlets leading to a rectangular exit of 5/16-inch height by 5/8-inch width. The impingement surface is constructed using 3/8 inch thick aluminum to provide an isothermal surface and includes 3 pressure taps. The impingement surface is mounted at an angle of 30 degrees from the direction of the nozzle flow and the surface is mounted on a pair of Velmex translation stages that allow the impingement distance to be varied and the location of the pressure taps to be scanned. The impingement distance was 2.25-inches, or 7.2 jet diameters. The pressure distribution along the centerline of the jet was measured using an incline manometer and this data will be used to compare the PSP results.

The first experiment was conducted using UniFIB. The jet plenum was set to 0.2-psi, this resulted in a maximum pressure on the impingement surface of 0.065-psi. The jet was allowed to operate for about 10 minutes to allow the system to reach thermal equilibrium and 20 wind-on images were acquired and averaged. The jet was turned off and 20 wind-off images were acquired immediately. The data was processed and the results are shown in Figure 7. The pressure distribution has the anticipated shape, a sharp rise in pressure on the upstream side and a slower drop in pressure on the downstream side. There is clearly an offset between the pressure tap data and the PSP data, this is most likely due to a small temperature change on the surface between the wind-on and wind-off data. As the aluminum is a good conductor and UniFIB is an ideal paint, this offset can be removed using a single pressure tap. A second experiment was conducted using Binary FIB; these results are shown in Figure 8. Here the bias between the uncorrected data and the pressure taps is a bit smaller but the overall results are similar. In each case the difference between the corrected PSP and pressure tap data is about 10% of the dynamic range of the experiment.

Results similar to these were demonstrated experimentally by Bell who presented quantitative data obtained on a Lockman wing at speeds as low as 17-m/s. In these experiments Bell presented results from both single channel and binary paint systems. Bell noted that the use of the binary paint increased the random error between the paint and pressure taps when compared to the single channel data. This increase in random error was noted as the natural result of the shot noise associated with the binary approach. Bell concluded that obtaining quantitative results at low speeds required very careful experimental techniques. That conclusion is supported here.

H. Automotive Mirror

A series of low speed experiments were conducted using an automotive mirror in the AFIT low speed wind tunnel. This is an open circuit wind tunnel with a 3 foot by 5 foot test section and a

Figure 7: Single Probe PSP data.

Figure 8: Binary PSP data.
maximum speed of Mach 0.2. An automotive mirror was outfitted with 6 pressure taps and mounted to a stand; the experimental setup is shown in Figure 9. The mirror was painted with three paint formulations, UniFIB, Binary FIB, and Dual-Lifetime FIB, and test were conducted at speeds of 30-m/s, 45-m/s, and 60-m/s. Results from the UniFIB test were of no value as there was substantial movement of the model between wind-off and wind-on measurements. Data from the Binary FIB system acquired at 60-m/s is shown in Figure 9. Note that at 60-m/s the tunnel dynamic pressure is about 0.3-psi and the range of pressures measured by the paint and pressure taps indicates a $C_p$ range of about 1. The PSP and pressure tap data compare very well in this case, the difference is about 0.02-psia or about 6% of the dynamic range.

Similar data was acquired on this mirror using the Dual-Lifetime system. The results for all three speeds are shown in Figure 10. The results in Figure 10 are very similar to those obtained using the Binary PSP. This should not be a surprise as the systems operate in a similar manner and use FIB based paints.

IV. Conclusion

While Pressure-sensitive paints can be used to obtain quantitative data at very low speeds, care must be taken to design the experiment in order to minimize several sources of error. These error sources include temperature, deformation/displacement of the model, and camera shot noise. The use of rigid models with good thermal conductivity is recommended to minimize model movement and produce an isothermal surface. Wind-off data should be acquired at conditions as neat to the wind-on images as possible. This generally means acquiring this data immediately after the wind-on images. Multiple images should be acquired and averaged to minimize camera shot noise. Binary paints are recommended in situations where model motion can not be eliminated or temperature gradients are significant.

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