PRESSURE-SENSITIVE PAINT: PRACTICAL APPLICATION IN WIND TUNNELS

Errol L. Yuksek
Colin P. Britcher, Advisor
Old Dominion University

Abstract

The use of Pressure Sensitive Paint (PSP) is one of the most effective methods of pressure measurement. Effective both on simple and complex surfaces, PSP can produce global surface pressure maps with exceptional spatial resolution. However, there are practical issues that hinder its accuracy. Surface preparation and paint application is tedious, expensive, and time consuming. Sensitivity to temperature is also an issue as it affects luminescent molecules and their transitions. Research has focused on developing self-adhesive tape or decals, pre-coated with PSP material. One advantage to this approach is quick and easy application to areas of interest during experimentation. This would not only minimize cost and surface preparation time, but simultaneously unveil a solution to the issue of PSP degradation. Should the PSP degrade from use or handling, one would need only to quickly remove the flawed strip and apply fresh PSP coated tape. Due to the more controlled conditions under which the tapes would be prepared, it would also be possible to apply dual coatings. For example: running a stripe of PSP along with a parallel stripe of Temperature Sensitive Paint would grant the ability to determine relative temperature and pressure measurements on a given surface. It would also allow for pressure measurement adjustments accordingly.

Introduction

Utilized primarily in wind tunnels, Pressure-Sensitive Paint (PSP) is an innovative pressure measurement technique. With its unique ability to provide a field measurement extended over the entire surface of a body, it can produce global surface-pressure maps with exceptional spatial resolution[3]. In order to obtain the highest quality surface-pressure maps with the greatest accuracy, an understanding of PSP's internal mechanisms, the experimental setup, and the properties and functions of experimental equipment were necessary. Also, a few facts and professional opinions concerning conventional pressure-measurement techniques and how they compare to PSP were appropriate.

PSP vs. Conventional Methods

According to Ford engineers, "A new way of measuring the external air pressures exerted on automobiles—pressure sensitive paint (PSP)—is faster and easier than pressure ports or computational fluid dynamics"[6]. Pressure ports and Computational Fluid Dynamics (CFD) are two common conventional pressure measurement methods.

The use of pressure ports is probably the first of the pressure measurement techniques ever utilized in wind tunnels[6]. Ford employed this technique on their cars, specifically the windows, in which they would remove the glass, replace it with a metal plate or plexiglas, and drill approximately 120 pressure ports. This tedious process would take at the least one week for a person to complete. According to Patsy Coleman, a senior technical specialist at Ford, "Typically, a [ridiculously] large number of pressure ports are used, and spaced about an inch apart"[6].

More advanced than pressure ports, CFD are computer simulations of real world problems[6]. These simulations are performed by creating virtual grids of a model's surface and calculating the pressure distribution along the grid. However, Ford engineers say, "Generating results from an average size grid might take days"[6].

PSP, on the other hand, provides full global surface-pressure measurements in only an average of fifteen minutes[6]. There is no need for drilling hundreds of pressure ports or waiting days for computers to *crunch numbers*. Stan Wallis, an aeronautical engineer with Ford, says, "This tool allows us to get more detailed pressure distribution information more quickly"[6]. The only drawbacks to PSP usage are its photo degradation and temperature sensitivity.

Internal Mechanisms

PSP is composed of luminescent molecules dispersed in an oxygen permeable, polymer binder[5]. Figure 1 shows that when PSP is exposed to blue or ultra-violet light, the luminescent molecules are excited to a higher energy state. From this state, they can decay in one of three ways: discharging light, transferring energy to the polymer binder (in the form of heat), or colliding with oxygen molecules at the PSP surface.

Since the luminescent molecules react with oxygen, they both collide with oxygen molecules and release light at the same time[5]. As a result, the amount of light emitted is inversely proportional to the amount of available oxygen molecules at the surface. Since collisions with oxygen molecules occur most frequently when the PSP is under a lot of pressure, the amount of light emitted is inversely proportional to the pressure at the surface.

The only drawback is the second possibility in which the luminescent molecules can transfer their energy to the polymer binder in the form of heat[5]. Inevitably, the heat transfer requires temperature increase in the polymer binder, thus causing the PSP to increase in temperature. Such an increase in temperature usually affects the luminescent molecules' ability to react with oxygen and results in false pressure readings. Fortunately, the effects due to temperature are slight in most cases, as the temperature may only rise by a few degrees.

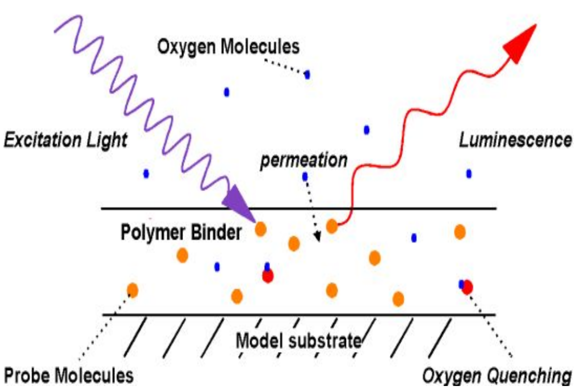

Figure 1. Illustration of PSP excitation, internal mechanisms, and response. Source ref [3].

Oxygen quenching, the actual driving mechanism for PSP, can be described mathematically through the Stern-Volmer Relation[3]:

$$\frac{I_{\max}}{I} = 1 + Kc \tag{1}$$

Where I_{max} is the maximum intensity in the absence of oxygen (c=0), K is the Stern-Volmer quenching constant, and c is the concentration of oxygen.

Since PSP is suspended within an oxygen permeable polymer binder, Henry's law can be applied within[3]:

$$c = SXP \tag{2}$$

Where S is the temperature dependant Henry's Law coefficient, X is the mole fraction of oxygen in the air, and P is the surface air pressure.

Substituting equation (2) in to equation (1), we obtain:

$$\frac{I_{\max}}{I} = 1 + KSXP \tag{3}$$

From equation (3), it is apparent that the intensity of the light emitted by the PSP is inversely proportional to the surface pressure and the mole fraction of oxygen in the air. Since K, S, and X remain constant in an experiment, we can produce non-dimensional pressure and intensity and introduce new constants:

$$\frac{I_o}{I} = A(T) + B(T)\frac{P}{P_o} \tag{4}$$

Where I_o and P_o are reference intensity and pressure respectively, and are obtained from a stagnant state. A(T) and B(T) are temperature dependant constants that can be obtained from calibration of the paint[3].

Experimental Setup

The experimental setup is the most important aspect of pressure measurement. For PSP, the setup consists of numerous components necessary for effective collection of pressure data. Essential components include an excitation light source, light filtration, camera, and a data acquisition system[2].

With the proper equipment, a PSP experiment proceeds in the following manner. The excitation illumination is emitted by a stable light source, typically of blue or ultra-violet wavelength. As the light illuminates the surface of the PSP, the luminescent molecules reach an excited state. Once excited, the molecules emit light of a singular wavelength, different from that of the excitation wavelength, and with intensity inversely proportional to the existing pressure at the surface. Because of camera sensitivity, the camera is fitted with an optical filter receptive only for the wavelength emitted by the paint. Finally, images taken by the camera are collected by a data acquisition system, and are subsequently processed to develop surface-pressure maps[2].

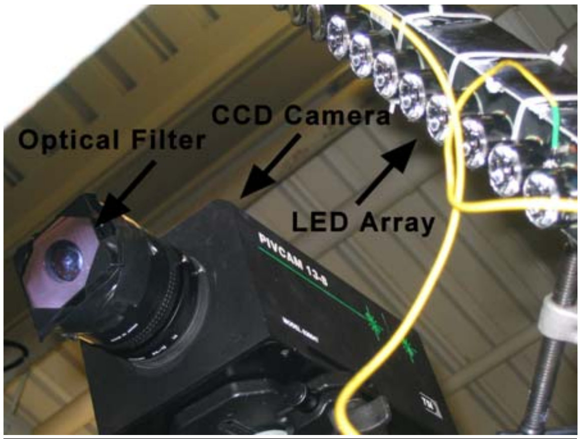

Figure 2. Photo of the equipment used; Optical Filter, CCD Camera, and LED Array.

Illumination

In order to excite the luminescent molecules in the PSP, an illumination source of the proper excitation wavelength was necessary. Also, shown in Figure 3, uniformly distributed illumination is important to maintaining constant excitation of the molecules, in order to guarantee a stable emission over time. If the illumination output were not stable, the molecules would change state in a non-uniform manner, thereby altering their reactions with the oxygen at the surface and resulting in erroneous pressure readings[3].

A common example of a stable illumination source used in a PSP experiment is a Light-Emitting Diode (LED). Its ability to emit stable wavelengths of light at high intensities makes them ideal for PSP excitation. For larger or more complex models with diverse surfaces, arrays of LEDs serve to illuminate all areas of a surface uniformly. This uniform illumination insures that every PSP molecule has sufficient energy to carry out reactions with the oxygen available at the surface[2].

Figure 2 shows an array of twelve LEDs that was used in the experiments. The wavelength was carefully chosen to be 405 nm such that it would provide the PSP with proper excitation. Also important, was the distance at which the lights were placed from the PSP specimen. In a first test the lights were too close, and evidence of accelerated photo-degradation on the surface of the PSP was apparent, resulting in non-responsiveness over time. (See Figure 6)

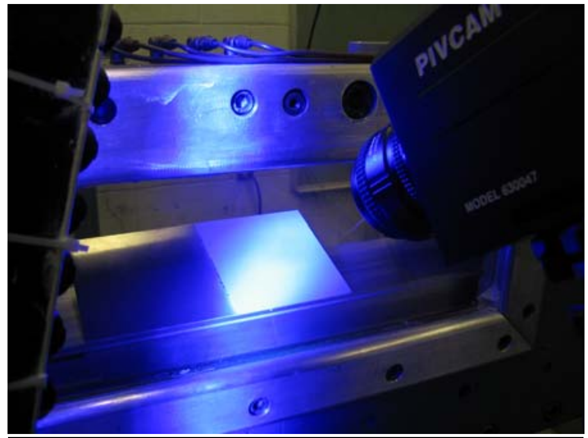

Figure 3. LED Array illumination of a PSP specimen in a pressure chamber.

Light Filtration

Due to the high degree of camera sensitivity and to avoid false pressure readings, light entering the camera must be limited to one wavelength. In a PSP experiment, there are many wavelengths of light present. These include the ambient light, the light produced by the LEDs (excitation spectra), and the light emitted by the PSP (emission spectra). Performing the PSP experiments in a dark environment eliminates ambient light. Since emission spectra are desired, an optical filter is employed to block the wavelength of the LEDs (405 nm) and admit the emitted wavelength of the PSP (650 nm). Once fitted with the optical filter, the camera is no longer subjected to interference by other light sources.

Camera

The camera is considered the most important component of any PSP experiment. Cameras used in PSP experimentation require a very high sensitivity to detect the small changes in emission intensity[2]. For this reason, a Charge-Coupled Device (CCD), or CCD camera, is typically chosen. Factors such as quantum efficiency and bit rate determine its accuracy.

Quantum Efficiency (QE) is defined as the rate at which the CCD chip converts photons into electrons[2]. This rate is largely dependent upon the cooling rate of the CCD chip. When an image is taken, the conversion of photons into electrons generates heat. Notably, this newly generated heat must be removed before the CCD chip can handle another conversion. Thus, the faster the CCD chip can convert photons into electrons, the more quickly and efficiently a CCD camera can acquire images.

Also, the camera's bit-rate is an important factor that determines the rate at which signals can be read from the CCD chip[2]. To each signal, a lifetime is attributed. This lifetime is a measure of how quickly a signal deteriorates. If the bit-rate is insufficient, data loss will occur. As a result, it is important that the bit-rate be adequate so that the signals do not deteriorate before they can be processed.

The camera shown in Figure 2 is a 12-bit CCD Camera with a resolution of 1280x1024 pixels and QE of 40%. Although not the best camera possible for a PSP experiment, the specifications were mid-range and sufficient for use in the tests performed.

Data Acquisition

As the CCD camera acquires images and sends them to the computer, they are stored for further analysis. Initially, the images sent from the CCD camera are monochromatic, typically in grayscale. Grayscale images are sufficient because changes in paint intensity can be measured by the variation of gray pixels[3].

Using standard graphical image software, a grey pixel average over a small test area was performed for calibration of the PSP. Figure 5 shows a test area of PSP responding over a 0 to 5 psig pressure range.

Pressure-Sensitive Tape

A number of observations were made while working with PSP. It is very watery and difficult to apply in a uniform thickness. Upon drying, it becomes very sensitive. It cannot be handled; the slightest remnant of oil from hands could result in pressure measurement errors. It peels and cracks easily if the surface upon which it is applied is deformed excessively. Storage of PSP must be strictly controlled. It must be kept from ambient light; otherwise, it would be subjected to an accelerated photo-degradation and decreased ability to respond in a test. Figure 4 shows the effects of over-exposure to ambient light on PSP over time.

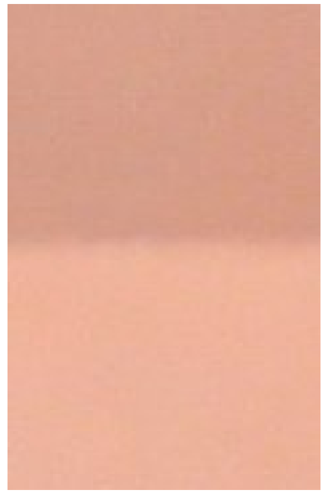

Figure 4. The upper portion of this PSP sample was left exposed to ambient light for 24 hours, while the lower portion was masked, keeping it intact.

Careful selection of substrate is necessary. Currently, tests have been performed only on rigid specimens; however, it is not difficult to expect that the substrate would require a high resistance to excessive stretching; otherwise, the PSP would undoubtedly crack or peel from its backing.

Conclusions

Working with PSP has been a great challenge and an even greater learning experience. Due to the optical nature of the experiments and PSP's properties and sensitivities, there were many probable sources of error. However, significant progress was made toward identifying and adjusting for them. Photo-degradation was dealt with by careful placement and positioning of the LEDs. Also, preparation of test specimens was performed in the absence of ambient light, making the probability for photo-degradation less likely. Much work still remains, and with patience and innovative ways around these obstacles, PSP has the potential to become the prevailing pressure-measurement technique used in wind tunnels.

Acknowledgements

I would like to thank Ilteriş Koç for his help throughout this research project, and for introducing me to Dr. Britcher. My gratitude goes to Dr. Britcher for his help and insight throughout the research. Many thanks go to the Langley Full-Scale Wind

Tunnel and Penske Racing, for inviting me to observe a full-scale PSP test on a *stock car*. Lastly, I thank the Virginia Space Grant Consortium for this invaluable research opportunity.

References

1. Gregory, W., Raghu, S., Sakaue, H., Sullivan, P. (2002). Porous pressure-sensitive paint for characterizing unsteady flowfields. *AIAA Journal 40*(6), 1094-1099.

2. Lee, S. (2001). Performance automotive applications of pressure-sensitive paint in the langley full scale tunnel. Un-published dissertation, Old Dominion University.

3. Pressure sensitive paint (2003). Retrieved November 26, 2004, from http://www.aerospaceweb.org/design/psp/main.shtml

4. Sakaue H., Sullivan, P. (2001). Time response of anodized aluminum pressure-sensitive paint. *AIAA Journal, 39*(10), 1944-1950.

5. Vandendorpe, L. (1997). Aerospace paints with a purpose. *R&D, 39*(6), 69-70. Retrieved October 19, 2004, from InfoTrac OneFile database.

6. Wiebusch, B. (2000). PSP gets pressure PDQ. *Design News, 55*(3), 25. Retrieved October 19, 2004, from InfoTrac OneFile database.

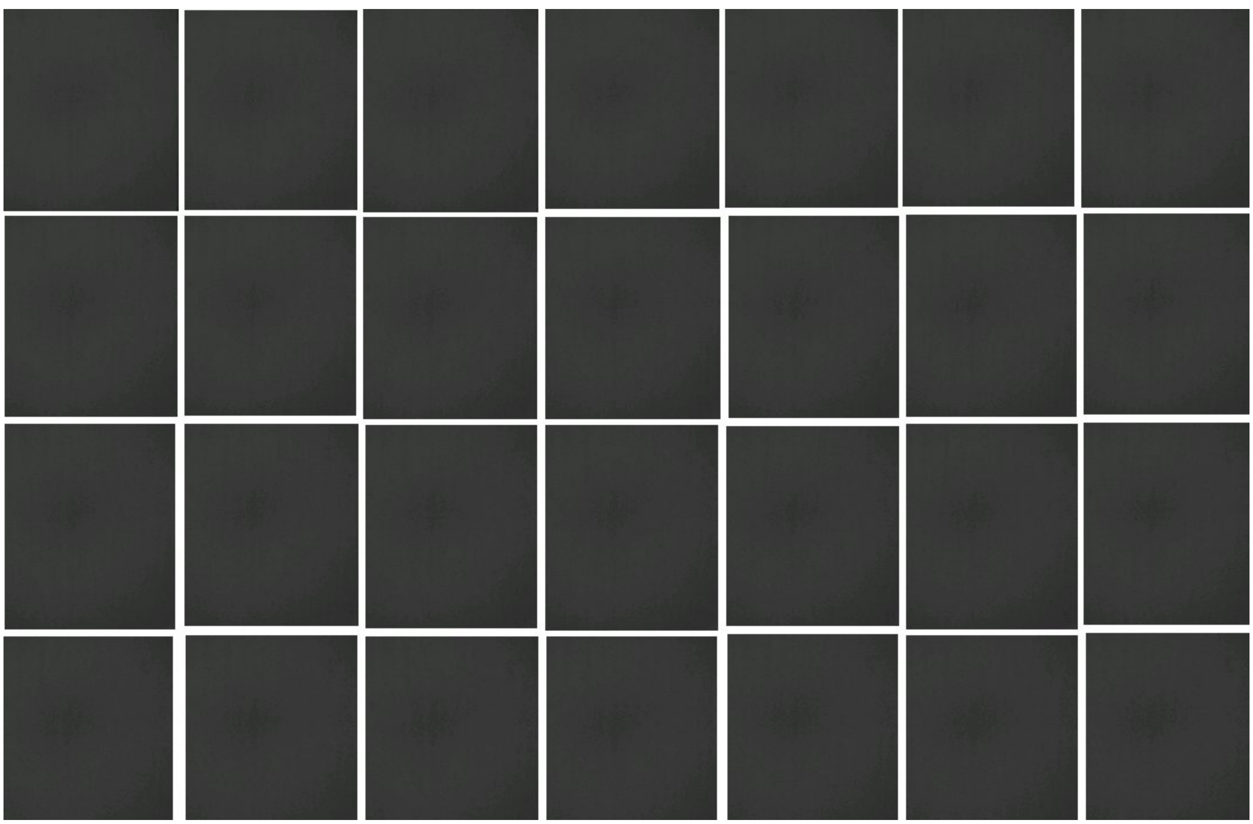

Figure 5. Test images of a PSP sample in a pressure chamber. Pressure increases from left to right, top to bottom, and varies equally between 0 psig and 5 psig. Close observation reveals the subtle change in intensity with pressure, which can be seen quantitatively in the grey pixel values.

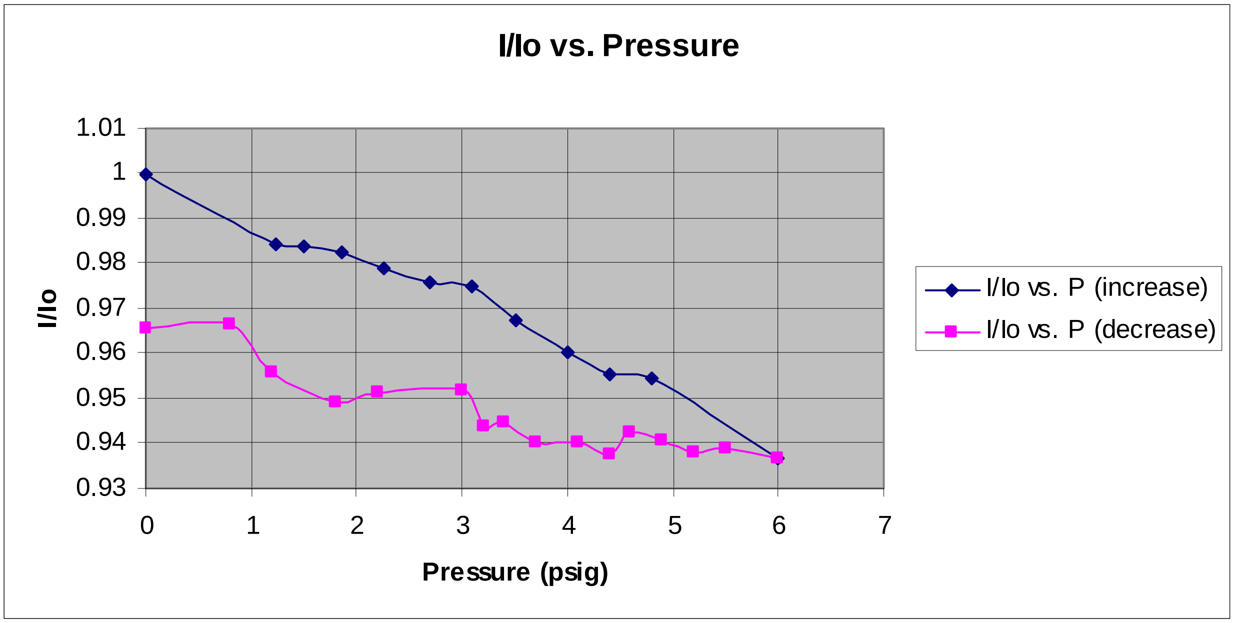

Figure 6. Photo-degradation as a consequence of excessive illumination.