

Pressure Resolution of a PSP Based Measurement System with Non-Linear Intensity Response

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An experimental study has been conducted at The Pennsylvania State University's Turbomachinery Aero-Heat Transfer Laboratory to develop an automated facility for calibration of Pressure Sensitive Paints (PSP). This paper deals with the calibration results of a particular PSP sample and their associated implications. Experimental setup of the facility and the calibration procedure have been briefly discussed. Results of this study, presented here in detail, reveal a unique character of the intensity ratio – pressure ratio relationship for the sample PSP. Rather than following the conventional linear pattern, this relationship was found to have a highly nonlinear character which was approximated with an exponential function using curve-fitting analysis. Repeated tests were conducted to confirm this observation. Such uniqueness of this relationship has a significant impact on not only the sensitivity range but also the pressure resolution capability of the paint. Since the intensity resolution of a PSP based measurement system is fixed (depending on the imaging device used), an exponential relation between intensity and pressure will lead to a variation in the corresponding pressure resolution over the whole range of pressures. In the present case, where a 10-bit CCD camera was used, such a variation was observed to be following a fourth-order polynomial function. Further, a simulated analysis for a 16-bit camera showed a significant improvement in pressure resolution for the same paint, although it still exhibited distinct variability over the complete pressure range. Finally, an error analysis was carried out over the different tests conducted as part of this study. Pressure values were estimated using the calibration equation and recorded intensity, and compared against measured values. It was observed that, in general, rms error increased as the pressure resolution of the paint decreased.

I. Introduction

PRESSURE sensitive paint (PSP) has been fast gaining recognition as an important experimental tool for optically and quantitatively measuring pressure. Due to the associated ease of setting up the complete measurement system and the amount of useful data that it is capable of providing, the PSP technology is seeing applications in both supersonic as well as subsonic flow regimes. However, in all its applications, the fundamental basis of this technology remains the same. Reflected intensity signals from the paint applied to the model surface are recorded at *wind-on* and *wind-off* conditions using a CCD camera and are subsequently converted into pressure values using a pre-determined calibration relation for that specific paint. Such calibration relation is commonly known as the Stern-Volmer equation and relates intensity ratio and pressure ratio of the known (*wind-off*) and the unknown (*wind-on*) conditions. In most cases, the Stern-Volmer equation is found to be almost linear with some temperature dependence which can

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be suitably overcome by keeping the temperature constant for the reference and the measurement condition. However, for certain paint formulations the calibration relation does not follow a linear trend. This property of the PSP, in such cases, gains significance since it directly affects the applicable pressure range for the paint and its corresponding pressure resolution.

A better understanding of the PSP behavior and the Stern-Volmer equation can be had by looking at the underlying physical processes which cause the PSP to respond towards any change in pressure in its surroundings. Navarra¹ provides a comprehensive description of such physical processes followed by their mathematical analysis. In a similar approach, Ingle and Crouch² and Dhall³ present their analyses based on the luminescence quantum yield (or efficiency), ϕ_L defined as the ratio of the luminescence radiant power to the absorbed radiant power where the radiant powers are expressed in photons per second. From its definition, ϕ_L will be dependant on the rate of both emission (luminescence) as well as absorption of photons. An elaborate treatment of these first-order processes has also been provided by Mosharov *et al*⁴ and Bell *et al*⁵ where luminescence has been analyzed considering the combined effects of fluorescence and phosphorescence. Using a few simplifying assumptions based on the fact that the rate of a first order reaction depends upon the concentration of the constituents, all the mathematical analyses reach at the basic form of the Stern-Volmer equation (Eq. 1).

$$\frac{\phi_F^0}{\phi_F} = 1 + K_q [Q] \quad (1)$$

where ϕ_F^0 and ϕ_F are the fluorescence quantum efficiencies in absence and presence of the quencher, respectively, K_q is the Stern-Volmer constant representing a combination of first-order rate constants of the different internal processes taking place including fluorescence, and $[Q]$ is the quencher concentration which is responsible for the quenching of PSP fluorescence. Since the luminescence quantum efficiency is defined in terms of photons per second, it can be directly related to the intensity of radiations (I), yielding:

$$\frac{I^0}{I} = 1 + K_q [Q] \quad (2)$$

Using Henry's Law to relate quencher concentration to pressure and acknowledging oxygen as the primary quencher in case of PSP fluorescence, the concentration of oxygen, $[O_2]$ can be written as:

$$[O_2] = S.P \quad (3)$$

where P is the air pressure and S is a temperature dependant Henry's Law coefficient. Further, in order to eliminate I^0 which is almost impossible to estimate, a ratio of the Stern-Volmer equation for two different conditions is taken where the reference condition represents the known condition. Hence, the final simplified form of the Stern-Volmer equation can be expressed as:

$$\frac{I_{ref}}{I} = A_0 + A_1 \frac{P}{P_{ref}} \quad (4)$$

A_0 and A_1 are known as the Stern-Volmer coefficients and since these are based on the definition of S, they too exhibit temperature dependency. Torgerson⁶ provides definitions for both these coefficients as follows:

$$A_0(T) = a_0 \left[1 + \frac{E_{nr}}{RT_{ref}} \left(\frac{T - T_{ref}}{T_{ref}} \right) \right] \quad (5)$$

$$A_1(T) = a_1 \left[1 + \frac{E_p}{RT_{ref}} \left(\frac{T - T_{ref}}{T_{ref}} \right) \right] \quad (6)$$

where E_{nr} and E_p represent the non radiative and polymer (binder) activation energies, R is the interaction distance and, a_0, a_1 are constants. An essential conclusion that can be drawn from Eq. 5 and Eq. 6 is that the temperature dependency of these constants can be effectively cancelled out by keeping $T = T_{ref}$.

Equation 4 is the most common form of Stern-Volmer equation that is used for PSP measurements due to linearity of the relationship between relative intensity I_{ref} / I and relative pressure P / P_{ref} . However, in case of some special coatings and under certain pressure and temperature conditions, this relation may no longer remain linear. As explained by McLachlan and Bell⁷, a more general form of Henry's law is required to explain PSP behavior in these cases. Accordingly the Henry's law coefficient, S is modified to include the effects of not only temperature but also pressure. This leads to a co-dependence of constants in Eq. 4 on pressure as well as temperature. In order to simplify the complex character of these constants, a polynomial expansion in pressure is used and the resultant, more general form the Stern-Volmer equation is written as Eq. 7. It is important to note that when used in this form, the Stern-Volmer equation retains its temperature dependency but attains a certain non-linear characteristic.

$$\frac{I_{ref}}{I} = A_0(T) + A_1(T) \frac{P}{P_{ref}} + A_2(T) \left(\frac{P}{P_{ref}} \right)^2 + \dots \quad (7)$$

In case of a PSP measurement system, the pressure resolution of the system essentially depends on the intensity resolving capability of the camera used. Using the paint's calibration relation, intensity information recorded for each camera pixel is converted to pressure values. Depending upon the bit depth of the camera (say N), reflected luminescence signal from the paint is recorded in a number of divisions (2^N). Each division corresponds to a particular intensity value and hence a particular pressure value. Difference between any two consecutive pressure levels, then, becomes the least decipherable pressure difference and hence the pressure resolution of the PSP system. However, in case a non-linear calibration relation, a constant intensity resolution of the camera will lead to a non-linear pressure resolution. This characteristic should be an important consideration while making measurements using the PSP system since a varying pressure resolution restricts the sensitivity and applicability range of the system.

A similar observation was made while calibrating a sample PSP using a calibration facility developed at the Turbomachinery Aero-Heat Transfer Laboratory at the Pennsylvania State University. This paper discusses the results of the calibration testing and focuses on their implications. The complete calibration process has been briefly explained followed by the results and their analysis.

II. Calibration Facility

Primary objective of this research study was to develop a PSP calibration system which could be used for accurately determining the correlation between a paint sample's luminescent response and the applied pressure. Calibration facility developed as part of this study has been schematically illustrated in Figure 1. PSP sample to be tested was applied to a base plate kept inside an enclosed calibration chamber. In order to provide optical access to the paint, the face plate of the chamber was made out of thick plexiglass. A pressure pump and a thermoelectric cooler were used to control pressure and temperature inside the chamber, respectively. Excitation illumination for the PSP was provided from a high intensity Xenon-arc lamp and the reflected luminescence signals were captured using a 10-bit, 1.3 million (1280×1024) pixels scientific grade CCD camera. In case of PSP testing, it is important to ensure that out of the complete spectrum of the excitation light, only the appropriate frequency radiations reach the paint. Similarly, the camera should be setup such that it captures radiations generated by the paint and no reflected part of the incident light. For this purpose, a blue colored bandpass filter (440 ± 5 nm) and a red colored longpass filter (600 ± 5 nm) were used with the lamp and the camera respectively.

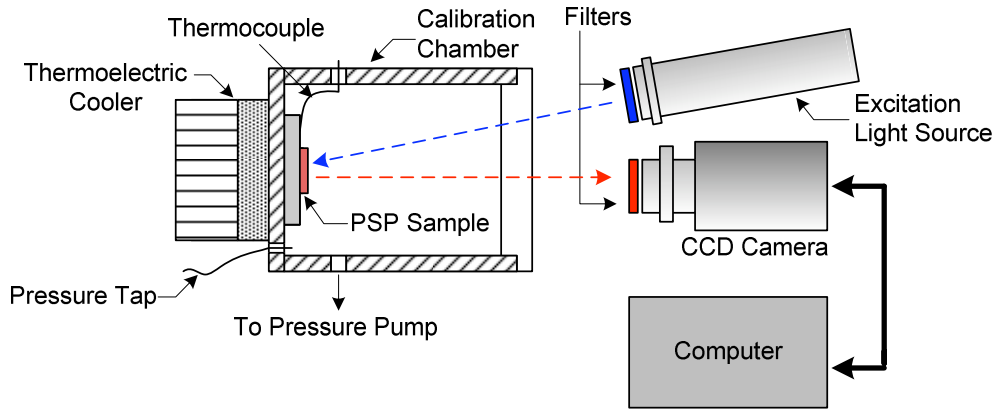


Figure 1. Schematic of the calibration facility

The paint sample used for this work was provided by the Innovative Scientific Solutions, Inc. (ISSI), Dayton, Ohio. The calibration procedure was carried out by varying the pressure inside the chamber in small steps from 5.5 psia to 21 psia (approx.) and recording the fluorescence signal from the paint at each step. Since, PSP response is known to be temperature dependant, each pressure cycle was repeated at different temperatures ranging between 18-40°C. In order to increase the signal-to-noise ratio (SNR), for each test six continuous frames from the camera were recorded and averaged. Following this, difference between intensity values for pixels corresponding to a certain region of interest in the averaged image and the background (dark) image are calculated and finally ratioed with difference of the image at atmospheric pressure (reference pressure) and the background image to obtain the intensity ratio for the tested pressure ratio (P/P_{atm}). This intensity ratio – pressure ratio data is evaluated analytically to yield a mathematical relation which serves as the calibration equation for the paint.

III. Calibration Results

Based on the procedure outlined above, a number of tests were carried out for the particular PSP sample. Although the major goal of these tests was to develop a mathematical formulation to relate the intensity response of PSP sample to test pressures, certain other essential aspects pertinent to PSP measurements like photodegradation, temperature effects etc. were also analyzed.

The camera recorded the response data from the paint sample by dividing the complete intensity range (from black to white light) in 2^{10} (=1024) divisions. Hence, the intensity observations from the image acquisition system were in terms of numbers ranging from 0 to 1024. Although, due to reflection of light and reduction of light intensity caused by the use of multiple filters, intensity readings were generally low. Each test was initiated by recording the paint response at atmospheric pressure. This was followed by changing the pressure and recording the corresponding response. In order to have a precise and detailed calibration plot, pressure was changed in small steps (~0.1 psi). Data from the image acquisition system was continuously passed on to the image processing software especially designed for this study for storage and further processing. This software focused on a certain region of interest (ROI) in every image and calculated the intensity ratio between the particular pressure image and the atmospheric pressure image on a pixel-by-pixel basis, in effect creating a 'ratioed' image. Since all intensity ratios in this ratioed image corresponded to the same pressure, their values were essentially the same. However, in order to be statistically correct, a histogram of all ratio values was plotted for every ratioed image and the value occurring the maximum number of times was selected as the final intensity ratio corresponding to that pressure. As a graphical representation of the results, a plot between all the pressure ratios (P/P_{atm}) and corresponding intensity ratios (I_{atm}/I) was plotted. This data was then analyzed through a curve-fitting routine to generate a mathematical relationship and hence provide the calibration equation. Further, in order to insure the repeatability and stability of results, several similar tests were conducted.

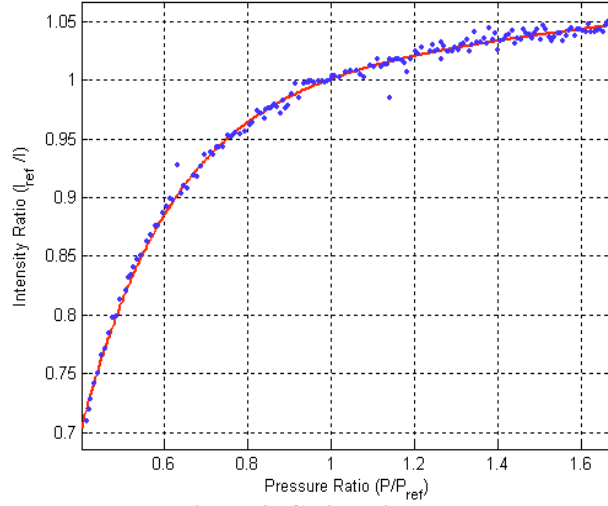


Figure 2. Calibration Results

Figure 2 shows the results of a particular calibration test in which each point represents the data obtained at separate pressures. Also shown in the image, is an exponential plot which was obtained by fitting the data to an analytical curve. This plot has been mathematically expressed in Eq. 8. It can clearly be seen that the data fits to the plot extremely well, especially for vacuum pressures. However, a small degree of scatter is also evident for higher pressures which can be attributed to the lack of a sophisticated control over generation of higher pressures in the calibration chamber and poor pressure resolution of the PSP for this range. Calibration results from other tests were also analyzed and corresponding plots have been shown in Figure 3. A similar exponential dependence exhibited by all the tests confirmed the repeatability and stability of the calibration equation.

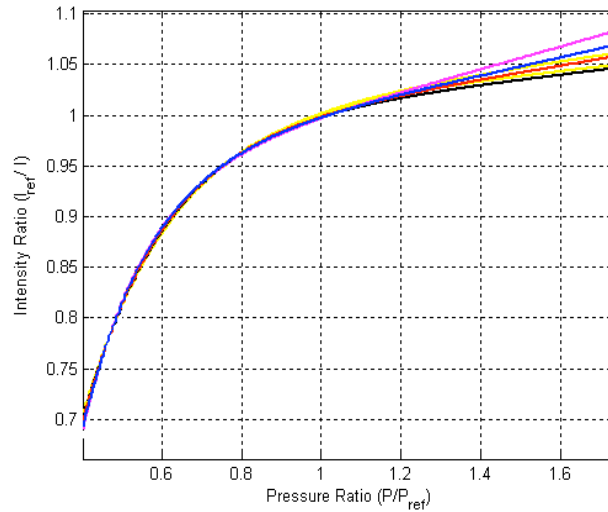


Figure 3. Repeatability of Results

$$y = a.\exp(b.x) - c.\exp(-d.x) \quad (8)$$

where,
 $a = 0.9814$
 $b = 0.03894$
 $c = 1.799$
 $d = 4.52$

Such an observance does not conform to the conventional and more commonly used linear form of Stern-Volmer equation relating intensity ratio and pressure ratio. This fact is further supported by Figure 4, which extrapolates the results of previous calibration test to both lower as well as higher pressures. The change in PSP response at higher pressures may be attributed to the phenomenon of luminescence saturation of emitted intensity which implies that if at a given pressure almost all the lumiphores present in the PSP layer are already being quenched, any further increase in pressure would not lead to a consequent increase in emitted intensity resulting in a constant or uniform response.

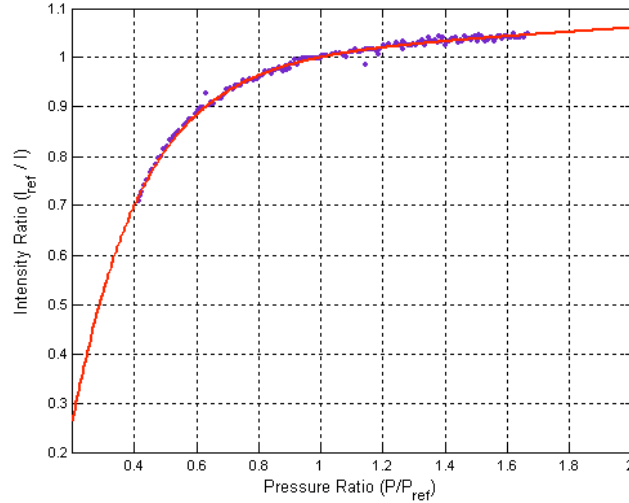


Figure 4. Extrapolation of Results

PSP is known to exhibit temperature dependence and in order to include the effect of temperature variations in the calibration equation, tests were also conducted at different temperatures. Figure 5 shows the results of three such tests conducted on the PSP sample for the same range of pressures. However, while analyzing and presenting the results care was taken to identify the reference point at the atmospheric pressure of the temperature at which the test was conducted. This step, in effect, eliminated the dependence of the calibration equation on temperature.

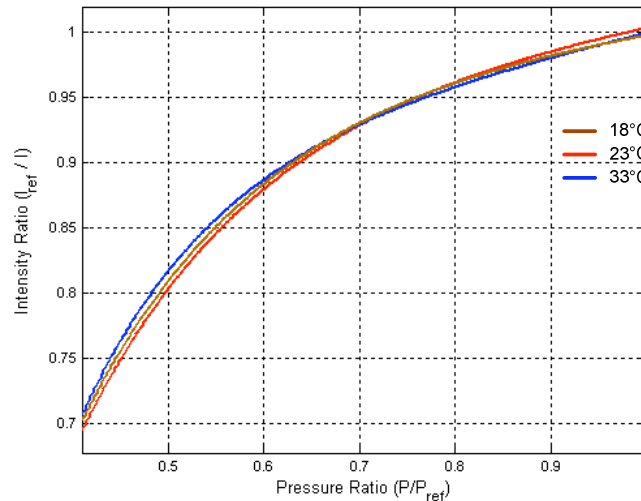


Figure 5. Temperature Effects

IV. Implications of Non-Linear Calibration Equation

A non-linear calibration equation will have a significant impact on the sensitivity and the pressure resolution capability of a measurement system designed using such a PSP. It is clear from the calibration plots that this PSP exhibits an enhanced sensitivity towards measuring vacuum pressures as compared to higher pressures. This fact puts limits to its range of measurable pressures and hence the overall applicability of the system.

The most important aspect of any PSP measurement system is its ability to yield spatially continuous and accurate pressure maps over a test surface. However, since the measurements are based on capturing intensity response of the paint and all the imaging devices have a definite limit to their intensity resolution, pressure distribution can also be mapped only with a certain minimum resolution. This minimum pressure is called the pressure resolution of the PSP measurement system. If, as in the current study, a 10-bit CCD camera is used for the measurements, the total number of intensity divisions available would be 2^{10} (=1024). Hence, the pressure resolution of that system would be the change in pressure corresponding to a unit change in intensity. This leads to a significant implication in reference to the non-linear calibration equation which has been shown in Figure 6 in terms of intensity vs. pressure instead of corresponding ratios. A unit change in intensity (ΔI) can lead to different changes in pressure (ΔP_1 and ΔP_2) depending upon the location of the point on the plot resulting in a variation of the pressure resolution of the system.

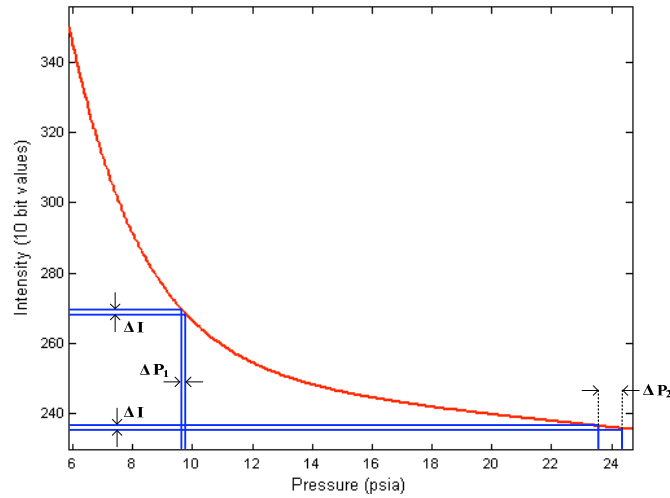


Figure 6. Variation of Pressure Resolution

In order to further investigate this variation of resolution, an analysis was carried out where using the previously obtained calibration equation change in pressure was calculated for a unit change in intensity for every intensity test point in the range of the previously conducted tests. The reference point data used for calculating intensity values from corresponding ratios was taken from the test. Owing to its transcendental nature, the calibration equation was solved numerically at every point to calculate pressure values from intensity data. The results of this analysis have been presented in Figure 8 where resolution capability of the system has been plotted against corresponding pressure values. This data was found to be following a polynomial curve of the fourth order (Eq. 9).

$$(PR) = a_1 \cdot (P)^4 + a_2 \cdot (P)^3 + a_3 \cdot (P)^2 + a_4 \cdot (P) + a_5 \quad (9)$$

where

$$a_1 = -2.423e-005$$

$$a_2 = 0.001171$$

$$a_3 = -0.01514$$

$$a_4 = 0.08969$$

$$a_5 = -0.1916$$

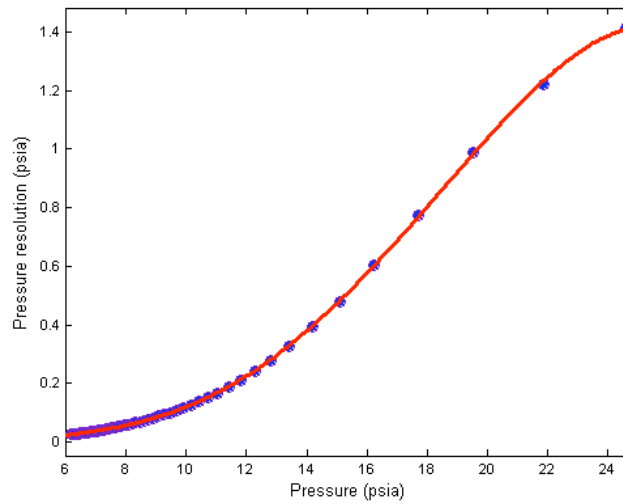


Figure 8. Variation of Pressure Resolution 10 bit

Two aspects are clearly evident from the plot. Firstly, the pressure resolution is not constant and varies along the range of pressure. Secondly, the resolution is only good for vacuum pressures and deteriorates steadily with increase in pressure to almost unacceptable values for higher pressures. Further analysis of this variation of resolution was carried out by simulating a 16-bit intensity capturing device. In this case, the intensity readings from before were simply multiplied by a factor of 64 ($=2^{(16-10)}$). Pressure resolution was again obtained using the same numerical procedure and the results, shown in Figure 7, exhibit a similar pattern of variation of resolution. However, a significant difference is evident in the scale of its values which is approximately 64 times enhanced. This leads to the conclusion that a CCD camera with higher bit depth is capable of providing improved pressure resolution for this PSP but it will still suffer from a definite pattern of variation.

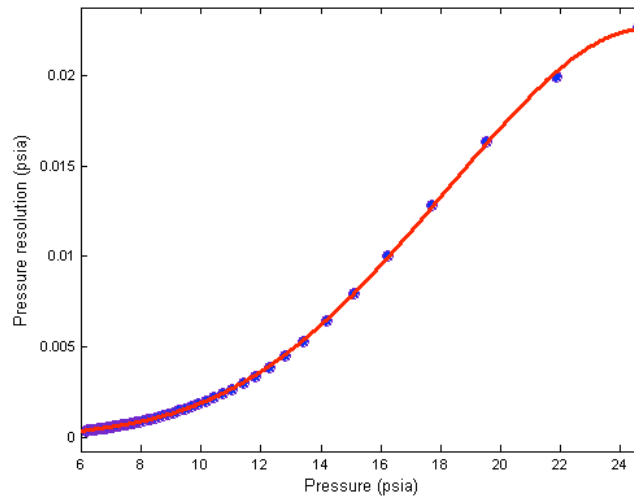


Figure 7. Variation of Pressure Resolution 16 bit

Finally, an error analysis was carried out over all the tests conducted in this study. Using the calibration equation and recorded intensity values, corresponding pressure values were estimated. Difference between estimated and recorded pressure values was noted down as the error. Figure 9 shows how the error level varied over the whole range of tested pressures. As can be seen from the plot, vacuum pressures can be predicted by the PSP sample more accurately and with less error than higher pressures. Rms error obtained from the distribution was 6.867 KPa, however, the same value for just the vacuum pressures was 1.674 KPa. This supports previous findings of this study which point towards inability of the paint to predict

higher pressures with a greater degree of certainty because of low pressure resolution. Further, owing to greater sensitivity and enhanced pressure resolution, relatively low error levels were observed for the vacuum pressures.

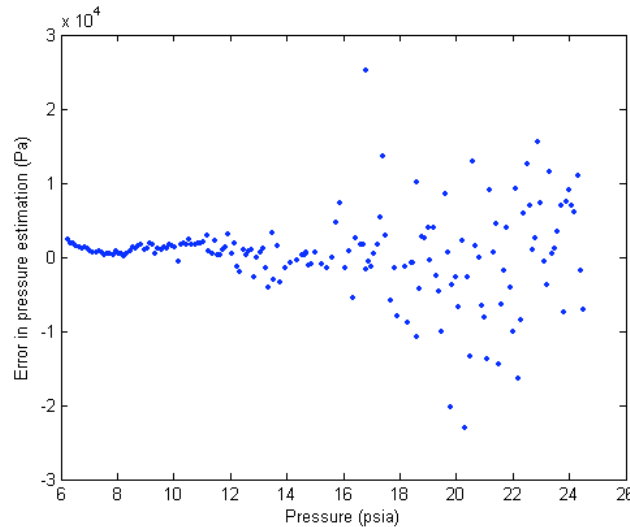


Figure 9. Error Analysis

V. Conclusions

Application and use of pressure sensitive paint (PSP) depends essentially on the calibration relation of that PSP. Conventionally, it has always been assumed that this calibration relation is basically a linear relation between the intensity and pressure ratios. However, by means of an automated calibration facility, this study revealed a highly non-linear calibration equation for a particular PSP sample. Greatest implication of such non-linearity was observed on the sensitivity and pressure resolution of the paint which limits the applicability range of this particular sample.

In conclusion, this paper emphasizes the importance of carefully calibrating the PSP before any application and setting the goals of that application in accordance to the sensitivity and pressure resolution of the paint.

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