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Dynamic Calibration of High Frequency Pressure Sensitive Paint

William Sealy[1] and Katya M. Casper[2]
Sandia National Laboratories, Albuquerque, NM, 87185

A dynamic calibration of High Frequency Pressure-Sensitive Paint (PSP) for application in aerodynamic research studies has been completed. Understanding of complex pressure field development for high-speed unsteady testing relies on compiled measurements from individual transducers, limiting the scope of results. High frequency PSP has been utilized in an effort to provide spatially and temporally resolved pressure fields. To validate response characteristics of the PSP, two test cases were carried out using an 8 kHz fluidic oscillator and Sandia's Multiphase Shock Tube. Results from impinging-jet fluidic oscillator testing have shown that PSP is able to accurately respond to frequencies up to 16 kHz. Preliminary shock tube data shows close correlation for pressure response between wall mounted pressure taps and the PSP in excess of 50 psi after temperature sensitivity correction.

Nomenclature

A, B, K	=	Stern-Volmer relation constants
I	=	luminescent intensity
I_{ref}	=	wind-off reference intensity
P	=	static pressure
P_{ref}	=	wind-off reference static pressure

I. Introduction

FLUID dynamics research has greatly benefitted from the advent of pressure-sensitive paint (PSP) as a diagnostic tool. This research relies on time-resolved aerodynamic force measurement to develop understanding of the underlying physics at work.[3] More specifically, high-fidelity pressure distribution information is desired for load measurement and to allow for analysis of flow phenomenon such as cavity tones.[2] The common method of obtaining this data relies on point measurements from individual pressure transducers. Despite the accuracy of these sensors, output data suffers from low spatial resolution. Measurements with PSP offer the ability to obtain high-resolution global pressure distributions not possible with these conventional pressure taps. Additionally, the PSP system minimizes flow intrusivity and greatly reduces cost and the amount of machining necessary to fabricate test models.[3]This text will address the calibration of a High-Frequency PSP system using fluidic oscillators and will extend the limited work done to investigate the time response characteristics of fast-response PSP in high pressure environments such as shock tube testing.

A. PSP

PSP is typically comprised of an oxygen-sensitive luminophore suspended in a supporting matrix. After being applied to the test surface the paint is excited with the appropriate wavelength and the luminescence is imaged through a long-pass filter by a CMOS camera. The oxygen sensitivity of the molecules causes the luminescent intensity to decrease as local oxygen concentration increases, known as oxygen quenching. The measured intensity can therefore be related to the local static pressure.[1,5]

Two main variants of PSP are available: conventional and porous PSP. The difference comes from the type of binder the systems utilize. Conventional PSP relies on a polymer binder layer that oxygen molecules must permeate

[1] Aeroscience R&D Intern, Engineering Sciences Center, P.O. Box 5800, Mailstop 0825 , AIAA Member
[2] Senior Member of the Technical Staff, Engineering Sciences Center, P.O. Box 5800, Mailstop 0825, AIAA Senior Member

through in order to interact with the luminophore molecules. Porous PSP systems utilize open binders that allow for direct oxygen quenching and therefore much more rapid response time to variations in local oxygen concentration.

For applications in supersonic testing that subjects models to rapid fluctuations of static pressure a porous fast response PSP developed by Innovative Scientific Solutions (ISSI) was used. The paint is a three component, single-luminophore high speed PSP that uses a platinum tetra-fluoro-phenyl-porphyrin (PtTFPP) and is applied with a ceramic-polymer binder. This hybridization allows the system to observe higher signal to noise ratios (SNR) at higher pressures.[5] The ceramic particles provide porosity to facilitate oxygen quenching while the small polymer concentration binds the paint to the model.

B. Dynamic Calibration

Two forms of dynamic calibration were completed with the PSP to analyze its response characterisitcs. First, a sweeping jet test was conducted using a fluidic oscillator. These devices produce oscillating jets at high frequencies with low flow rates and can be used to calibrate the paint response. Previous work has been done to characterize these devices for use in flow control applications with PSP as a validation diagnostic.[4] Results in these works show agreement between porous PSP power spectra and fluidic oscillator behavior up to 21 kHz. The second and final calibration utilized the quick pressure step environment of a shock tube.[1] Shock tube calibration has been done with fast-response PSP formulations in order to measure response times in the μsec range that cannot be observed in simple pressure step chambers. However, most work has been done to characterize PSP response time in comparison to sample thickness at final pressures nearing 101 kPa. In order to expand upon that work, tests were run covering post-shock ranges up to ~186 kPa. Resultant pressures occurring after the contact surface and reflected shock passed rely on initial driver pressure and ranged up to ~903 kPa.

II. Experimental Setup

Figure 1 shows the experimental setup for the impinging jet calibrations. All tests were completed with ISSI's Fast Porous PSP (FP-PSP) and applied to an aluminum baseplate using ISSI's specified procedure. The test cell was vacuum sealed and attached to a vacuum line to allow manipulation of test pressure during static calibrations. Additional ports were open for shop air and sensor lines. Cell windows were made of fused silica to minimize excitation light attenuation during testing. Excitation light was provided by two ISSI LM2XX-DM-400 water-cooled arrays which produce excitation light near 400 nm (± 30 nm) and provide 8-12 W of power. Local light intensity greatly effects the signal to noise ratio of the paint, as luminescent intensity is directly related to excitation light intensity. Therefore, both arrays were fitted with collimators to limit spreading and increase local light intensity.

A Kulite (XCQ-062-50A) pressure transducer was embedded into the testing plate below the jet port of the fluidic oscillator. The sensor output was passed through an Endevco Model 136 DC Amplifier which provides signal excitation of 10 V and gain of 100.[2] The resonant frequency of the sensor is 240-300 kHz and sampling frequency is just below that at 200 kHz. To attenuate high frequencies, a 100 kHz low-pass Bessel filter was used.

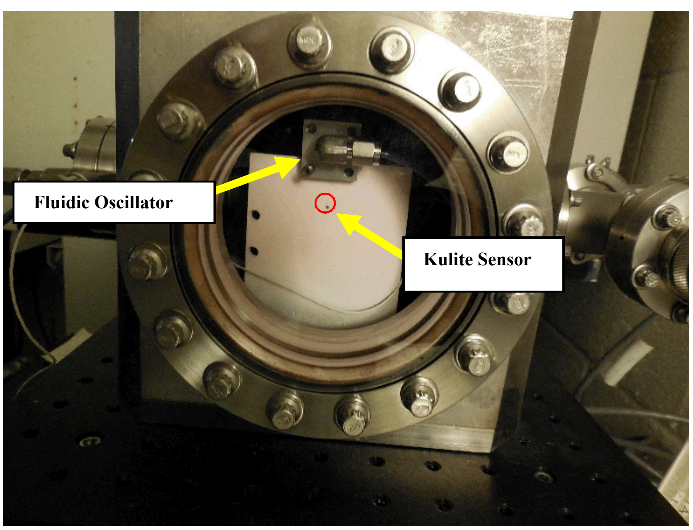

Figure 1. Test cell setup for sample calibration and testing.

To fully image the sample, a Photron SA-Z high speed camera was used. The camera was fit with a 50-mm lens and a 590-nm long-pass filter to separate 400 nm excitation light from PSP emission which is observed in the ranges of 600 to 720 nm. Imaging was completed at 100 kHz with a resolution of 640x280 and the camera was positioned normal to the test surface and in line with the front window of the test cell. This configuration allowed for full imaging of the beginning of the impinging jet to the sweep over the embedded Kulite transducer. Kulite data, after being amplified, was recorded by a Tektronix DPO7000C Series Oscilloscope. Testing was completed at a line pressure of 20 psia.

A. Static Calibration

Before dynamic testing could be completed, a relation had to be made between paint luminescent intensity and pressure. The test cell is vacuum sealed and capable of maintaining pressures near 700 mTorr. To create reference pressure profiles, the paint was statically imaged at atmospheric pressure within the test cell and subsequently lower pressures were cycled via vacuum pump until near-vacuum (~700 mTorr) was achieved. Test pressure was then cycled back up to atmosphere to observe any hysteresis effects. At each pressure step the paint was excited with the two water-cooled arrays for a brief instant to avoid rapid photodegredation. Both the LED arrays and the CMOS camera were connected to the same digital delay generator (Stanford Research Systems Model DG645) and run from a single pulse trigger that allowed simultaneous activation of recording and paint excitation.

Recorded luminescence was converted to pressure readings using an intensity-based method in which a ratio of the "wind-on" and reference (wind-off) images in conjunction with known test pressures determined the governing equation for that specific test. In the case of static calibration, the wind-off image is the beginning static test case at atmospheric pressure and the wind-on images are the subsequent pressure steps. The governing equation is the linear Stern-Volmer relation[6] shown in Eq. (1),

$$\frac{I_{ref}}{I} = A(T) + B(T)\frac{P}{P_{ref}} \tag{1}$$

where I_{ref} and P_{ref} are the intensity and pressure wind-off reference conditions, respectively; I and P are the intensity and pressure wind-on conditions, respectively; and A and B are calibration coefficients determined through testing.

Results from the static calibration yielded calibration coefficient values in the ranges A = 0.3-0.4 and B = 0.6-0.7 that can be seen in Figure 2. R^2 values fell above 0.99 showing close correspondance to expected linearity. Processing of raw images was done through MATLAB and used a linear time-invariant filtering command (wiener2 algorithm) to reduce unwanted image noise. This process was implemented in previous static calibrations with much success.[2]

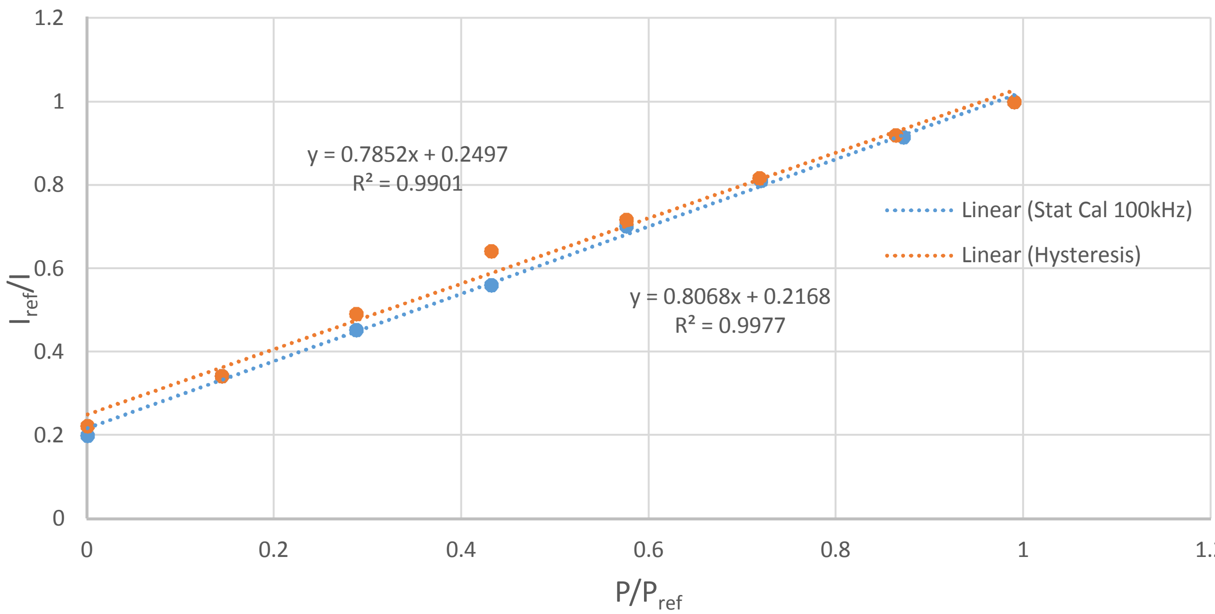

Figure 2. Static Calibration Curve for Fluidic Oscillator Testing.

B. Multiphase Shock Tube

To measure the pressure-step response of the PSP, Sandia's Multiphase Shock Tube (MST) was used.[7] The MST is a modular shock tube experimentally capable of producing incident shock Mach numbers nearing Mach 2 at 600 psi. Further pressurization is possible but so far remains untested. The shock tube has an 89 mm diameter driver section at a length of 2.1 m. This section connects to a Dynamics Systems Research (Model 183-1.5-2000) fast acting gate valve. This valve eliminates the need for a time-consuming burst disk system and allows for variable ranges of driver pressure to be run, consequently allowing for incident Mach numbers and convective flow velocities to be more precisely dialed in. Beyond the valve lies the 5.6 m long modular driven section that houses the attached test section and pressure transducers.[7] The MST surge tanks hold compressed nitrogen for testing. However, the nitrogen lines were swapped for house air lines when it was realized the increasing concentration of N_2 near the paint was slowing O_2 quenching and therefore causing a luminescent saturation. The issue became evident when routine checks of specific pixel locations before testing tracked an increase in reference intensity rather than a slight degredation as expected from the PSP. Additionally, tests run at high driver pressures saw pre-shock saturation resembling a vacuumed environment that invalidated recorded data. This anomaly was caught early and a full suite of air-driven runs was established. Because the gate valve runs by default on a nitrogen release, a system was established to vent test gasses after a run, vacuum the test section down to the mTorr range, and then vent the test section back to atmosphere using a ball valve release.

PCB 113B27 (top), Kulite XCQ-062-50A (middle), and PCB 132A31 (bottom) pressure transducers were used as a reference for the paint calibration. The location of these sensors can be seen in Figure 3. The sensors are attached to the test plate after application of PSP has been completed. Figure 3 also shows the arrival of the incident normal shock in the first image to the arrival of the reflected shock in the last image.

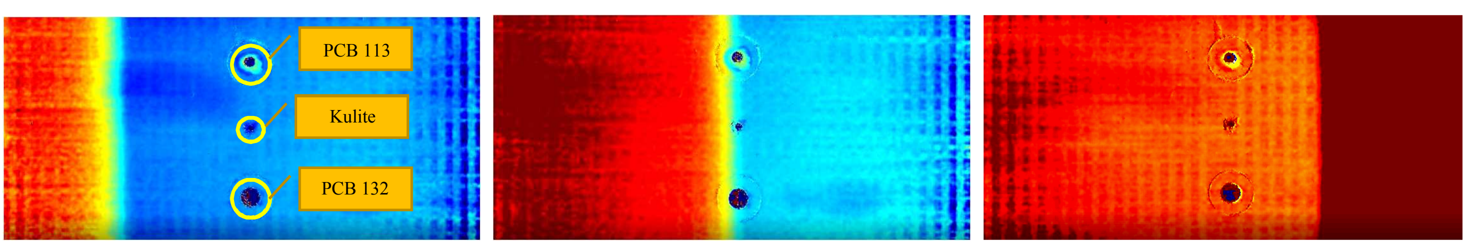

Figure 3. Shock progression (left to right) along test section wall showing additional PCB sensors (top and bottom).

III. Experimental Results

A. Fluidic Oscillator

Figure 4 illustrates the PSP response to increasing pressure as jet sweep progresses in fluidic oscillator testing. Jet sweep direction is marked by arrows for visualization and the Kulite sensor is marked with a red circle. Images were normalized at atmospheric pressure (left) to help with the visualization of pressure increase across the sample. Non-uniformity in surface pressure distribution can be seen developing longitudinally along the plate as the sweep progresses.

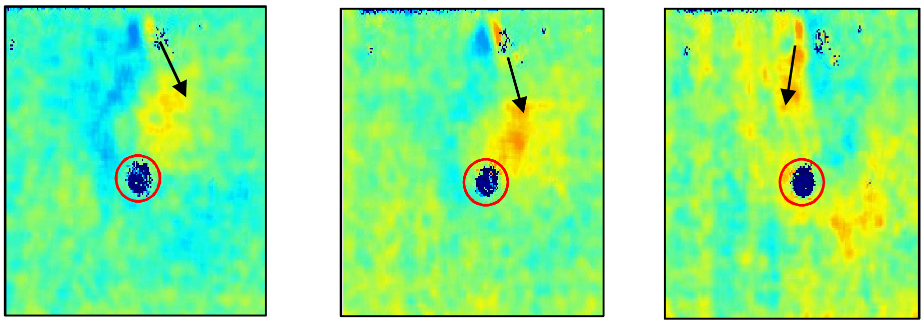

Figure 4. Jet sweep visualization during 20 psia run with normalized pressure.

Figure 5 shows the computed PSD of the test data for comparisons between oscillatory frequencies measured by the PSP and the Kulite sensor. Results from fluidic oscillator testing show agreement between primary and harmonic frequencies at 8 and 16 kHz respectively. Measurements of sensor noise would need to be taken to determine whether the dip in energy of the PSP at high frequencies can be attributed to low response capabilities or whether the PSP is exhibiting a lower noise floor.

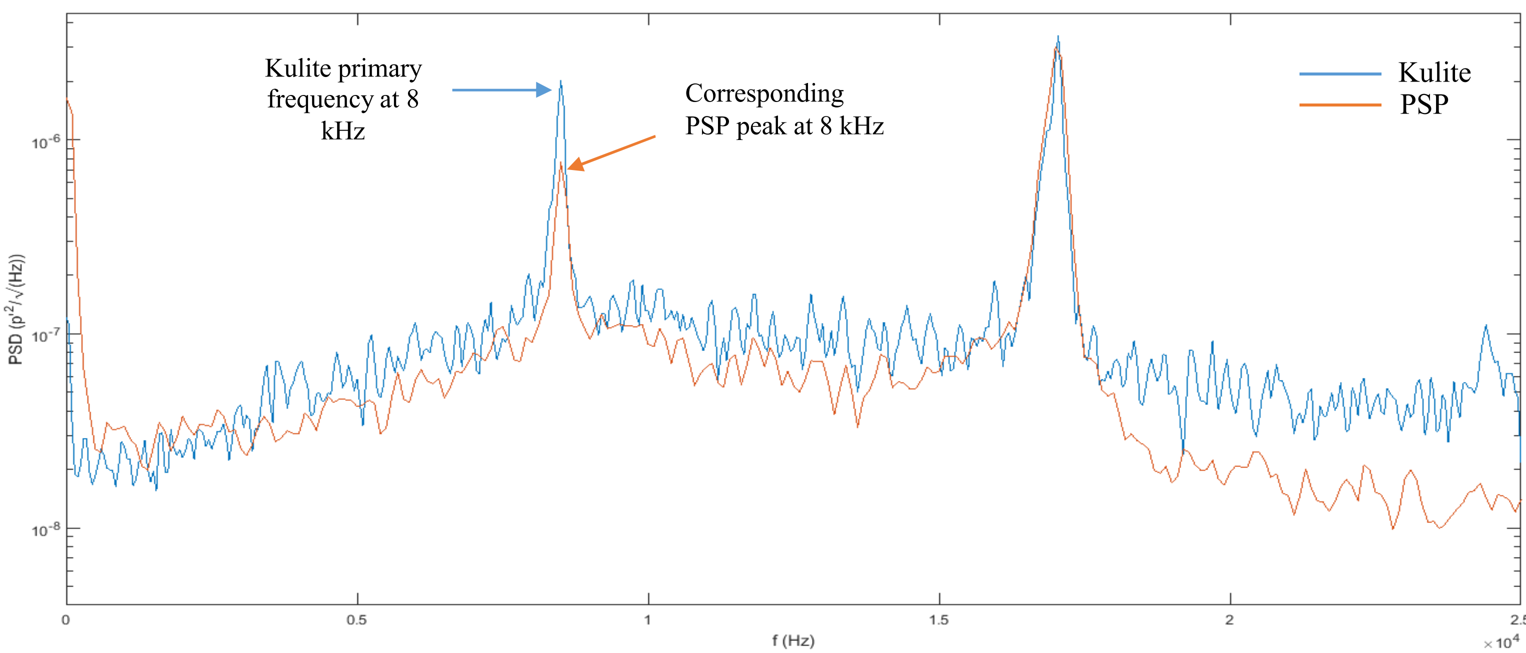

Figure 5. PSD of PSP and fluidic oscillator data illustrating matching primary frequencies and harmonics at 8 kHz and 16 kHz respectively.

Comparisons of time trace data for the PSP and Kulite can also be seen in Figure 6. A 20 μs delay is observed in peak occurrences within the data and is attributed to the delay between jet sweep arrival to the Kulite and PSP patches. The two data sets show good correspondence and track well for the fluctuations being observed during testing. Observed amplitude differences do not typically exceed 0.1-0.2 psia. To compare PSP time traces to Kulite data a representative 13x13 pixel section of the PSP sample was time-averaged, where 13x13 pixels roughly incapsulated the image area of the Kulite.

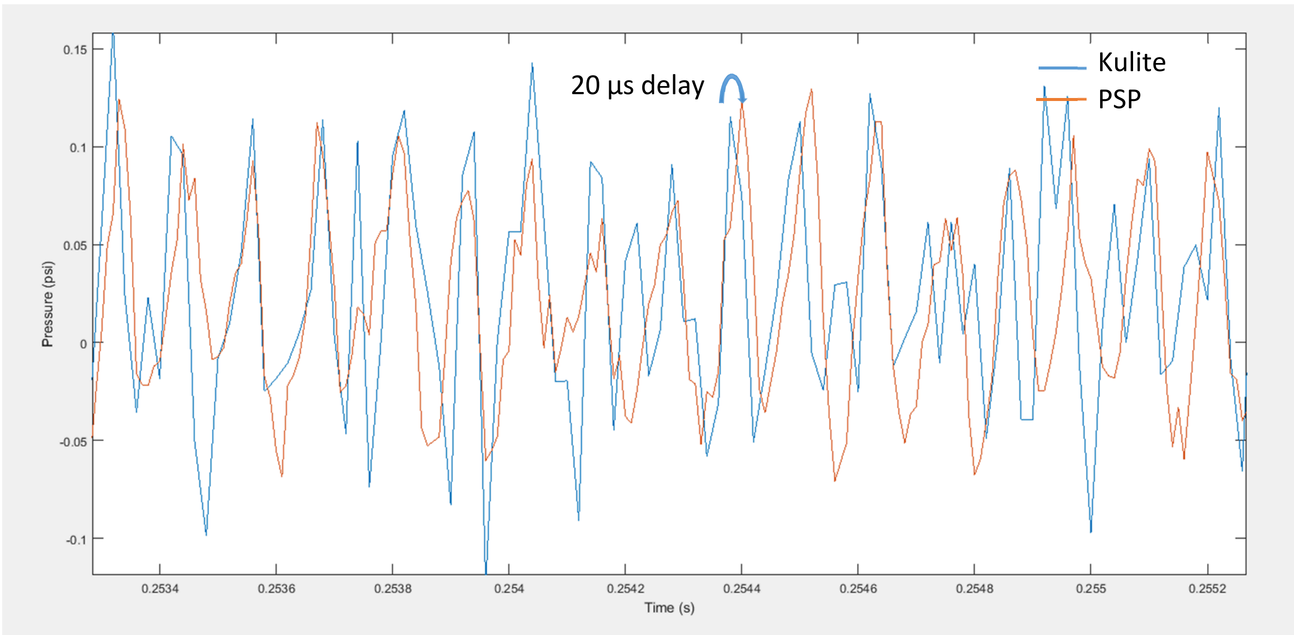

Figure 7. Kulite and PSP pressure trace comparison showing 20 μs delay in peak-to-peak correspondence.

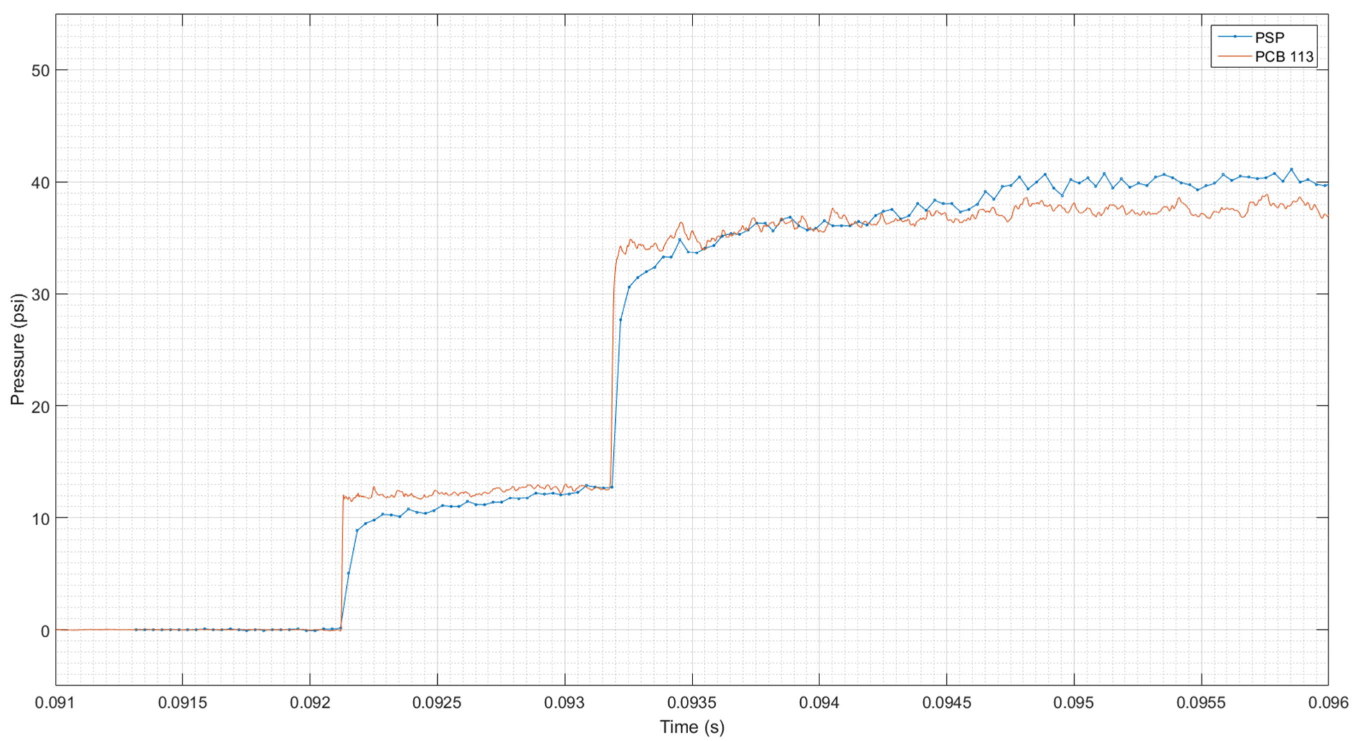

Figure 6. Full pressure trace without temperature correction.

B. Shock Tube

Figure 7 shows a co-plot of pressure traces for all three in-plane sensors and the PSP at a driven pressure of 12.09 psia and a driver pressure of 87.14 psia producing an incident shock at Mach 1.36. It can be seen that the PSP responds to shock incidence along with the PCB and Kulite sensors however at a much slower response rate. This lag can be somewhat remedied by increasing PSP imaging frequency to attain more data points during shock arrival but will ultimately be limited by the diffusion of oxygen through the paint binder. Despite response lag, the PSP is shown to match post-shock pressures. After meeting final pressures, the PSP exhibits pressure overshoot. This overshoot is caused by the temperature sensitivity of the paint formulation.

C. Temperature Dependence

Fast PSP exhibits a drastic temperature dependence and in testing, porous fast response PSP has a temperature sensitivity of 3.6% per °C.[8] Figure 7 displays a run in which temperature correction was not taken into consideration. This decrease in observed luminescent intensity without correction projected a higher static pressure than what was actually being experienced during testing. Figure 8 below shows the same run with an assumed linear temperature correction of 0.04° C/frame applied at an initial atmospheric temperature of 22.54° C. This method is a rough correction performed in absence of real-time wall temperature data but serves to correct the previously observed overshoot. The correction was achieved by using MATLAB code that digitized published correction curves from ISSI and created a interpolating fuction capable of updating calibration coefficients in real time with temperature variance and subsequently updating P/P_0 values to match the correction. Figure 9 shows the correction curves as output by the code.

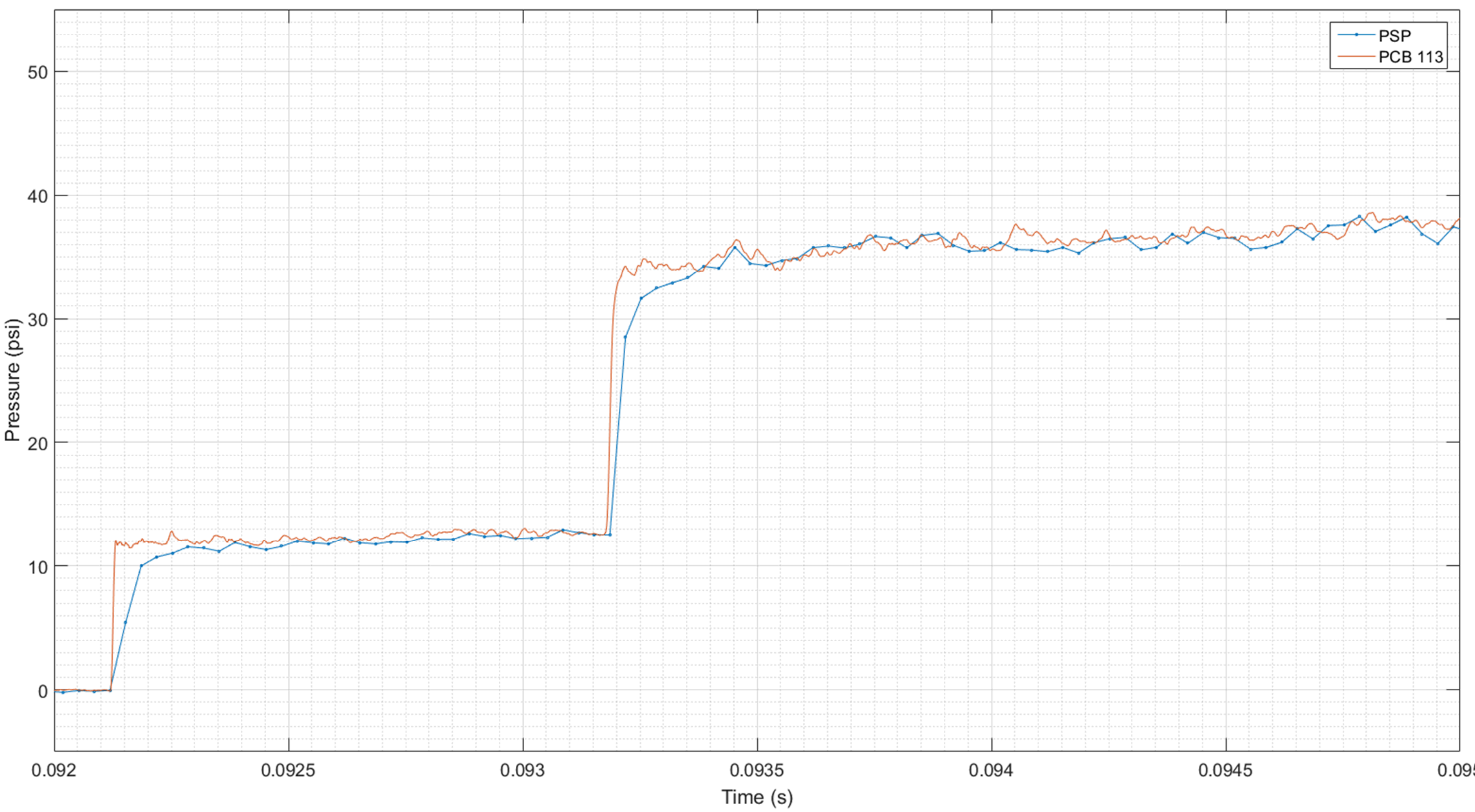

Figure 8. Temperature corrected PSP trace with coplotted PCB 113 readings.

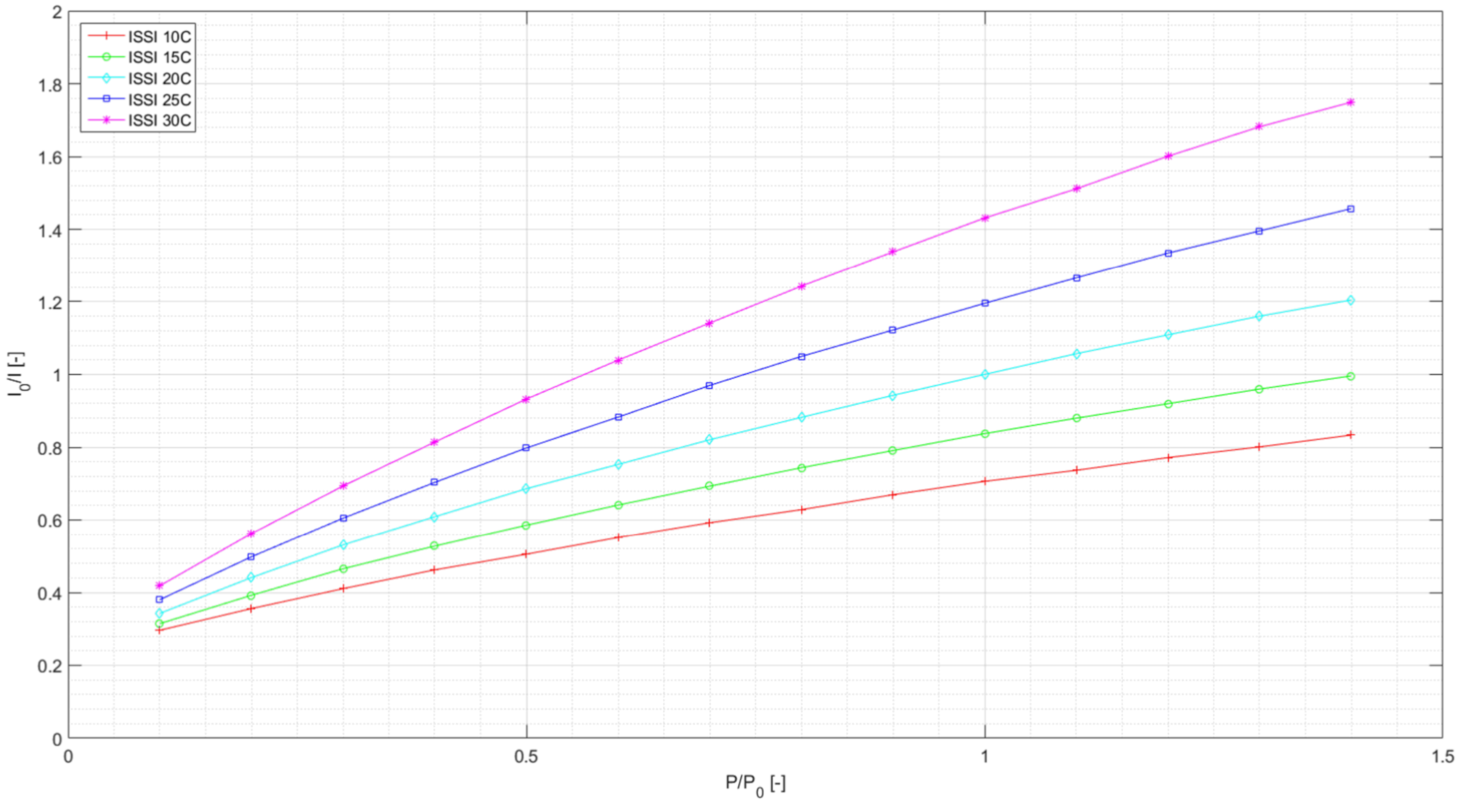

Figure 9. Digitized calibration curves for High Frequency Pressure Sensitive Paint.

IV. Conclusion

In this research a fluidic oscillator and multiphase shock tube were used to examine the pressure response characteristics of a porous pressure sensitive paint. In fluidic oscillator tests, the High Frequency PSP w showed agreement for frequencies up to 16 kHz when observed in comparison with a conventional Kulite pressure transducer. Behavior of the PSP shows a deviation in response beyond this frequency. Pressure amplitude differences from PSP-Kulite time traces were in the range of 0.1-0.2 psia and these results reinforce the viability of PSP application in low pressure oscillatory flow fields.

After correction for test section nitrogen saturation during shock tube testing, a successful test regime was established using air as the driven gas. Although temperature correction is needed, preliminary testing for high pressure step response of polymer-ceramic PSP shows efficacy in matching post-shock pressures in excess of 50 psia. At an imaging frequency of 30 kHz, a preliminary linear correction of 0.04° C/frame has been implemented to smooth data. More analysis of the paint is necessary to fully expand upon the temperature dependency in high pressure step environments. A real time temperature analysis is needed with an embedded thermocouple in the test fixture to provide an accurate correction curve. This data would allow for ISSI's specific temperature corrections to be made.

Acknowledgments

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