Pressure-Sensitive Paint Measurements of a Hypersonic Vehicle

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The application of pressure-sensitive paint (PSP) is a vital experimental validation method in the development of hypersonic vehicles during the design and testing phase. PSP is coated on test articles to obtain a continuous surface pressure distribution that is otherwise unattainable with electrical pressure transducers. Such pressure distribution will provide a clearer picture of the aerodynamic loads experienced by hypersonic aircraft during flight. PSP is excited by a UV light emitting diode (LED) and emits light in the visible spectrum at different intensities as a function of local pressure. Wind tunnel experiments with the PSP method are being carried out at the Mach 7 Ludwieg Tube facility at the University of Texas at San Antonio (UTSA). This manuscript describes the employment of the PSP technique on a hypersonic vehicle concept model, which was developed by the Air Force Research Laboratory (AFRL) and is called Initial Concept Three-Phase (IC3X). The fast response, steady state PSP implemented in these experiments is previously mixed and calibrated in-house. Images of the IC3X captured with a high-speed video camera and processed to analyze pressure fluctuations on the surface of the model are showcased. PSP efforts will support NASA's ULI Full Airframe System Technology (FAST) in the development of new measurement techniques that provide a global in-flight aerodynamic state and will buttress current Schlieren imaging and simulation results.

Nomenclature

I_o = Reference Intensity
P_o = Reference pressure

I. Introduction

The pressure sensitive paint (PSP) technique has been researched and developed since the 1970's [1]. The advantage that this non-intrusive technique offers is the ability to obtain global surface pressure distributions of models experimentally and at a relatively low cost, as compared to intrusive techniques like pressure taps that provide a discrete amount pressure measurements that cannot be averaged to obtain a representative pressure distribution. [2]. Multiple wind tunnel facilities around the world are implementing the PSP technique due to these advantages to study steady and unsteady surface pressure distributions. Results from PSP measurements can be used to validate CFD results and provide training data for aerothermoelastic simulations that are in current development. [3] PSP is excited by UV light with a Light Emitting Diode (LED) usually in the overlapping spectrum of the UV and visible light at 400 nm wavelength. This excites the PSP and this one emits light in the visible light spectrum centered at 650 nm [3,4]. The intensity at which the light emits is a function of the amount of oxygen present reacting with the paint and can be directly related to pressure [4]. Fast PSP is suitable for high-speed applications such as hypersonic wind tunnel testing where the test times are in the order of milliseconds [5]. The pressure sensitive paint technique is being implemented at the UTSA Mach 7 Ludwieg Tube Facility with the IC3X concept hypersonic model and will contribute to the ULI FAST project goals. The ULI FAST project seeks to develop a measurement configuration within the frame of hypersonic vehicles to obtain in-flight aerodynamic load information during flight testing. The results form the application of the steady PSP carried out at UTSA will give experimental insight on the pressure distribution of a hypersonic vehicle, will aid in finding the solution to the inverse problem of translating pressure distribution into aerodynamic load distribution and will contribute to the development of hypersonic aircraft development.

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II. Experimental Program

A. Experimental Facility

The PSP tests with the IC3X model were carried out at the Mach 7 Ludwieg Tube Wind Tunnel facility at UTSA. This facility operates on a pressure differential to drive the flow into the test section. This is achieved by first drawing the full system down to a vacuum using a Sogevac SV65B pump and then utilizing a MAX-AIR 35 electric compressor with a 4.2 SCFM charge rate to pressurize the working fluid into diaphragm rupture [5]. The vacuum pump draws the full system down in ~45 minutes, while the compressor pressurizes the driver tube at a steady rate of ~68.95 kPa/min. The driver tube is 18.29 m (60 ft) long and rated for a maximum pressure of 13.79 MPa (2000 psia) [7]. Six Omega Pressure Transducers (PX319-3KGI) with a range of 1 standard atmosphere to 20.79 MPa (3000 psig) along the driver tube length are used to determine the target pressure [5]. The test section floor has two pressure taps, one is located closer to the model and the pressure measurements are taken with an Omega pressure transducer rated for pressures under 106.67 kPa (15.4694 psia) with a response time of less than 1 ms and an MKS piezoelectric vacuum transducer with a response time of less than 40 ms. For a hypersonic application, the MKS transducer response time is too slow. However, due to its superior accuracy, it is implemented to calibrate the Omega transducer readings. An Omega pressure transducer in the plenum is connected to a module that triggers the data acquisition equipment in less than 9.78 ms ± 0.5 ms after a 36.86 kPa ± 4.62 kPa (5.346 psi ± 0.67 psi) rise in pressure that results from diaphragm rupture and indicates the beginning of a run. [6]. The high-speed images were recorded with a Photron SA-Z Fast Cam. The pressure sensitive paint was excited using an Onforu ultraviolet (UV) light emitting diode (LED) centered at 400 nm with a pulse frequency of ~60 Hz and 100 watts of power. A parabolic reflector and diffuser was implemented in front of the UV LED to focus the light into the surface coated with PSP. Lastly, two filters and AR filter with 450 nm interference and a PSP 610 nm filter where placed in front of the camera lens to only allow the light that the PSP emitted to go into the camera and filter out bands outside of the emission range.

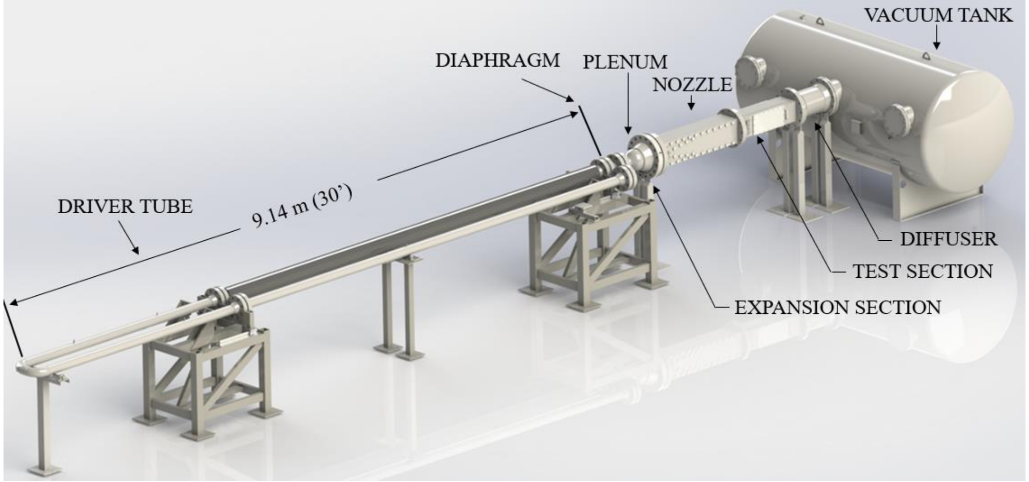

Figure1. Rendering of the Mach 7 Ludwieg Tube Wind Tunnel Facility at UTSA.

B. 3D Printed Model

The IC3X model is a concept hypersonic vehicle designed by the AFRL and it is the model that the ULI FAST project is using across its teams to be able to compare the results of their experiments. The geometry of this model was outlined in detail in Ryan J. Klock's dissertation [8]. The dimensions of the full-scale model were scaled down in order for the fin thickness to be able to be printed with the smallest nozzle available without compromising the geometry. The 3D model was printed out of a polycarbonate filament, a material that was strong enough to withstand the wind tunnel test without breaking. Fig.2 depicts the render of the UTSA IC3X model and Table1 contains further details of the model dimensions and properties.

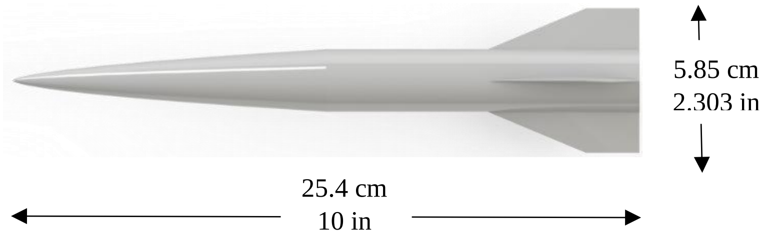

Figure2. Rendering of the UTSA IC3X 3D Model

Table 1. UTSA IC3X 3D Model Properties

Property	SI Units	English Units
Body length	25.4 cm	10 in
Body diameter	1.64 cm	0.645 in
Wingspan	5.85 cm	2.303 in
Mass	45 g	0.099 lb
Young's modulus	2048 ± 66 MPa	
Tensile Strength	59.7 ± 1.8 MPa	
Bending Modulus	2044 ± 55 MPa	
Bending Strength	94.1 ± 0.9 MPa	

C. Pressure Sensitive Paint

The fast steady pressure sensitive paint utilized in this experiment was developed by Innovative Scientific Solutions, Inc (ISSI). It is a single luminophore, porous PSP with a response time of less than 100 microsec, therefor allowing for acquisition rates of at least 10 kHz. The paint specification sheet describes that this paint works best when it is excited by UV light in the range of 380-nm to 550-nm centered at a 400 nm wavelength and emits visible light in the range of 600 nm to 720 nm centered at ~655 nm. [9] The paint comes in three separate parts; part A and B are mixed to make the under layer and part C is an overspray that is applied after the under layer has dried. The paint was mixed in-house at a chemistry laboratory with available fume hoods to apply the paint safely. The paint was applied with a high-pressure low volume (HPLV) spray gun at with a pressure regulator to spray at 172 kPa (25 psia) using a 758.4 kPa McGraw compressor.

D. Paint Calibration

The was calibrated in house, by coating PSP on the test section floor and using it as a vacuum chamber to record high-speed images at 10 target pressures. Three sets of images were collected for each target pressure. These sets of images were acquired at 1 kHz, and due to the pulsing LED, some of the images varied in intensity at the same pressure. The dim images were filtered out using a threshold reduce the set from 6000 images to a set of the 100 brightest images that shared a consistent intensity. The resulting sets of 100 images were averaged to obtain a single image for each set that was collected. This produced 30 images of calibration data points. The 30 measurements of the 10 target pressures were taken in a random order to avoid hysteresis in the results. The average intensities of the three images corresponding to a single pressure were averaged and resulted in 10 total discrete pressure measurements and their intensity. In order to fit a curve that better represent the relationship between the intensity that the pressure sensitive paint emits as a function of the local pressure, the resulting 10 discrete measurements where then normalized using each measurement. This normalization technique not only prevented bias that could be produced from using one normalization point over another, but also produced a total of 100 points to make a more robust curve fit. Fig. 3 depicts the 100 discrete points from the calibration experiments and the logarithmic fit that the data followed.

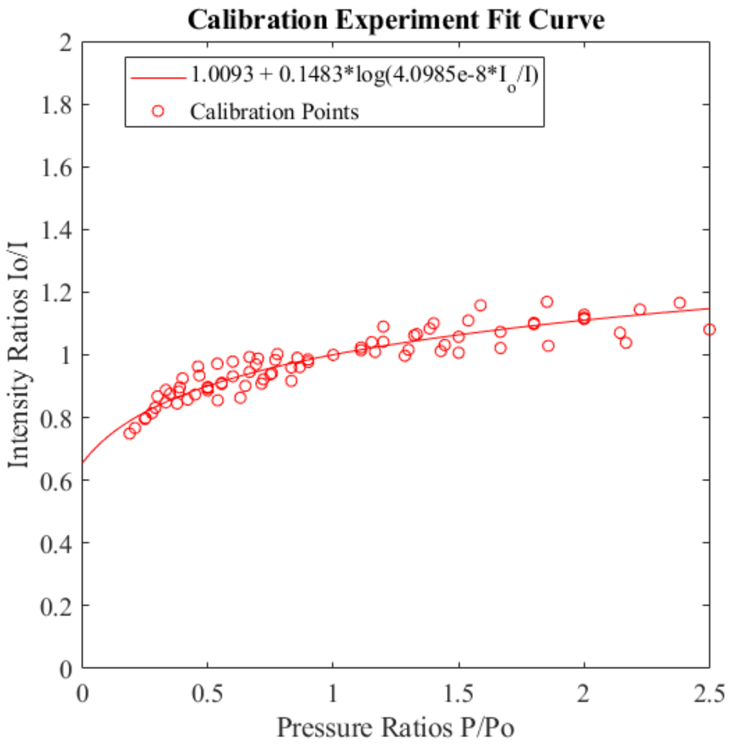

Figure 3. PSP Calibration Curve Fitting

E. Experimental Setup

The images of the fast PSP coated IC3X during the wind tunnel run were taking by placing the camera lens center in line with the model centerline, perpendicular to each other. The wind tunnel area was dark. The only light that was on, was the UV light, that was placed as close to the test section as possible while avoiding reflections from the test section that were visible in the images. A reflector-diffuser was placed on the LED surface to focus the UV light into the model and avoid scattering. An AR and a PSP filter were placed on the lens surface to filter out the wavelengths that did not correspond to the PSP emission band. Fig. 4 shows the experimental set up as seen from the top view of the facility.

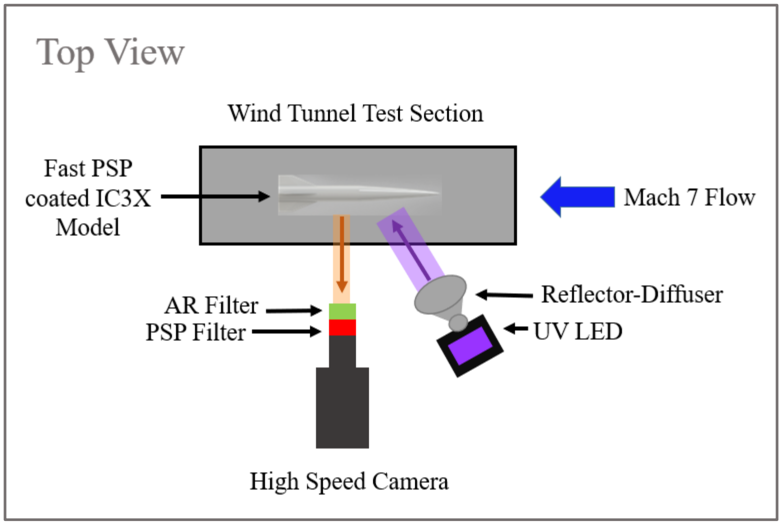

Figure 4. Diagram of the UTSA PSP Experimental Set Up

III. Results and Discussion

A. Image Processing and Pressure Results

The images produced on this run were obtained using a center trigger on the high-speed camera. This trigger setting allowed us to record images before diaphragm rupture, while the test section is under vacuum, and after rupture, which is when the model undergoes Mach 7 flow. As mentioned previously, the data acquisition equipment, including the camera, are triggered by a module able to sense the diaphragm rupture. When the camera is triggered to begin recording, it outputs a voltage signal with a clear spike. This signal was used to match the data from the pressure transducers with the high-speed images to determine the set corresponding time before diaphragm rupture, the “wind off set” and the set corresponding to the time after, the “wind on” set. This sentence confused me. The high-speed camera recorded 1000 frame rates per second, hence, producing one image per millisecond. This image acquisition rate was selected to record the greater number of images while keeping them visible. Despite this, due to the LED lower frequency, the images varied in overall intensity, with some being completely dark. Fig.5 shows the distribution of average intensities for the wind off and wind on sets with the average intensity thresholds that were used to select the brightest images that would best represent the pressure fluctuations.

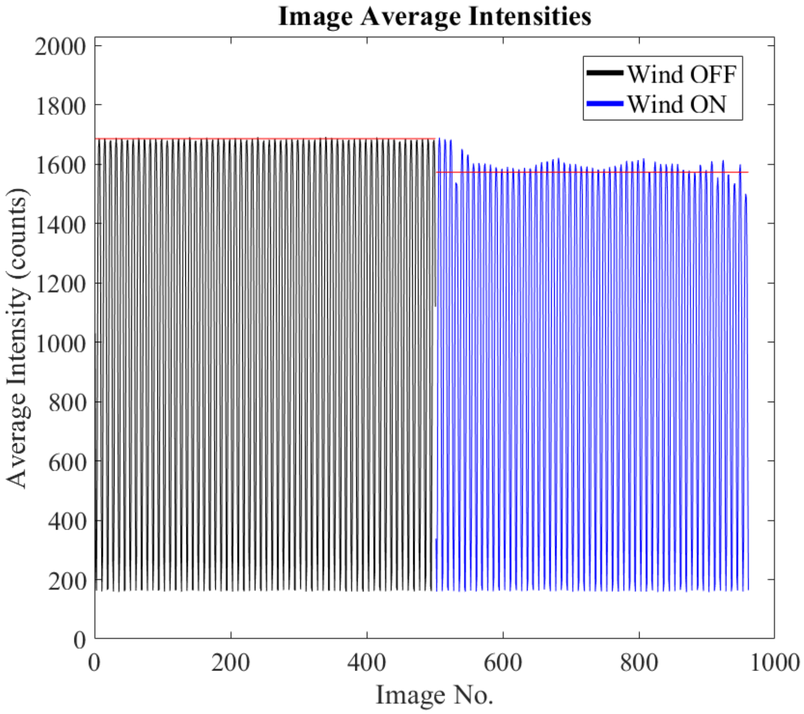

Figure 5. Full set of image average intensities with threshold

As noted from the graph above, PSP emits higher intensities at lower pressures, thus, when the test section was under vacuum, the paint emitted a constant intensity, higher than when the hypersonic flow comes in and increases the pressure in the test section. Therefore, the wind off and wind on stacks had a different threshold at which the images that fell below were not considered. A set of 560 images pre-run were reduced to the 20 brightest images and averaged to obtain a single image, which was used as a reference. The average intensity of full image area was used as the reference intensity I_o. Similarly, the pressure in the test section was recorded before diaphragm rupture, while it was at a vacuum. The readings of the high-accuracy vacuum pressure transducer MKS corresponding to 500 ms before rupture were averaged and this result was used as the pressure reference P_o. The P_o for this wind tunnel run with the IC3X model was 368.2 Pa (0.0534 psia). The wind on image set contained 400 images before reducing them to the 80 that were considered for the analysis. The average intensities of the selected images were normalized by the reference intensity value, and the resulting intensity ratios were used as input to the calibration curve fit to obtain the corresponding pressure ratios. Fig. 6 shows the intensity ratios of the images plotted against the pressure transducer readings and the calculated pressure based on the pressure ratios that were output of the curve fit.

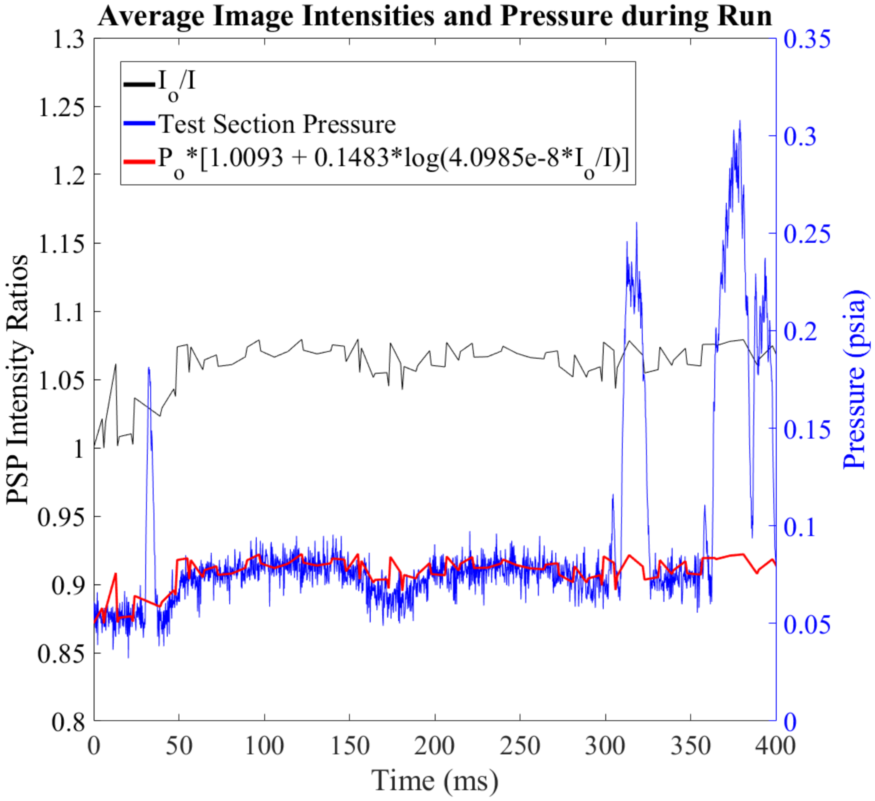

Figure 6. Image intensities and pressures during wind tunnel run

The graph presented above depicts that the calculated pressures were in agreement with the pressure transducer readings, which gives confidence that the PSP that was coated in the model was sensitive to the global pressure fluctuations with a small margin of error. The calculated pressures were 1.02 times higher than the measured ones. Furthermore, background division was performed on the images observe the surface pressure distribution in the model. The images corresponding to the first steady state pass were averaged and then divided by the wind off averaged image. Fig. 7 Shows the result of this division with the curve fit output pressure ratios.

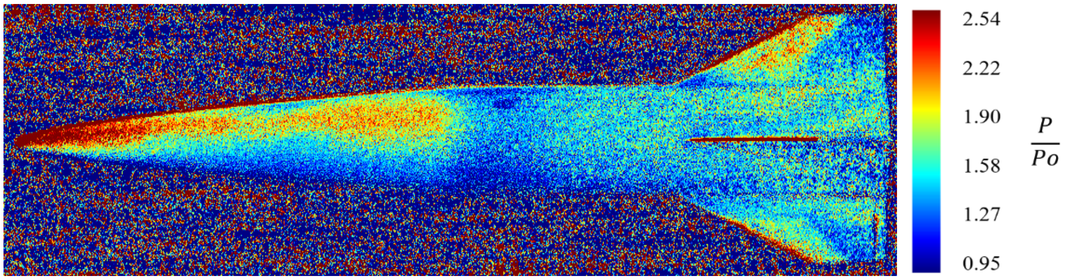

Figure. 7 IC3X pressure distribution during the first steady state pass

The surface pressure distribution that is visualized in the model agrees with the expected based on compressible flow theory and previous Schlieren images of the model. As seen in fig. 7, the nose experiences high pressure due to a leading shock. Further downstream, an expansion fan is produced as a result to the geometry change from an ogive to a constant diameter cylinder that results in a low-pressure region as seen in the middle of the model. The flow is compressed when it comes into contact with the leading edges of the fins and a shock interaction happens in the rear of the vehicle.

B. Temperature and Paint Degradation Considerations

The temperatures of the model and test section need to be taken into consideration when analyzing the results. Fast PSP is not only sensitive to pressure, but also sensitive to temperature. The intensity of the light that the paint emits is higher with increasing temperatures [10]. The temperature of the facility remains relatively consistent across the runs [11]. Since both the calibration experiments and the wind tunnel test were ran at room temperature, a temperature adjustment was not considered. During the test, the test section is subject to a significant drop in temperature, however since the test time is less than 300 ms, the time for heat transfer is insufficient and the paint emits light as a function of the internal driver tube temperature before diaphragm rupture.

In addition to considering ambient temperature, time of exposure and paint degradation due to decay can significantly affect the pressure results. Pressure sensitive paint experiences photodegradation as short as per minute of exposure and simultaneously decays with time that causes the paint to emit light at lower intensities than it would when it had just finished curing. Due to the non-linearity of the degradation, there is a need to calibrate the paint before it is tested or ensure that the paint that is to be tested is the same age as the paint was used for calibration. The results of the IC3X runs presented in this paper correspond to paint that was relatively the same age. This is confirmed by the agreement in the measured and calculated pressures. Further tests are required to quantify the significance of both paint degradation and temperature across the tests.

D. Plans for Improvement

A significant limitation to more accurate results were the specs of the LED available at the time of the tests. The research group acquired a more powerful, continuous UV LED that will allow to fully take advantage of the fast response time of the paint and acquire at a rate no lower than 20 kHz, and the ability to use the full set of recorded images. The calibration and wind tunnel test presented here will be reproduced to obtain time resolved pressure distributions. The number of images will also allow to perform further analysis such as convergence analysis to determine results with more accuracy. In addition, new calibration method has been laid out so that it is performed in less time and allows to increase the number of discrete pressure and intensity points. This will reduce the effects of photo degradation and decay with time. Lastly, the 3D model surface finish will be iterated to observe more representative pressure distributions of a full-scale hypersonic vehicle.

IV. Conclusion

The results presented in this manuscript confirm that the preliminary implementation of the PSP technique was successful at sensing pressure fluctuation sin the model. The pressure rations that resulted from the curve fit with the logarithmic model agreed with the data obtained from the pressure transducer in the test section. Changes in temperature and paint age did not affect the agreement of the results, therefore, they were negligible. These preliminary results show that the PSP is sensitive to pressure, and the current experimental method and results are a prelude to more refined analysis. These results will be used to validate CFD and provide training data for aerothermoelatic machine learning simulations.

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