Guide for Pressure-Sensitive Paint Testing at NASA Ames Research Center Unitary Plan Wind Tunnel

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Optical measurement techniques have become a standard option for wind tunnel tests. Pressure-sensitive paint (PSP) is a mature test technique and a common experimental technique in many wind tunnels to measure the global mean static pressure on a model. PSP is a valuable tool when a more detailed distribution of the pressure is needed rather than the conventional pressure taps alone. Planning for a test with optical-based techniques can present new challenges even for experienced customer. The purpose of this paper is to provide a resource to the wind tunnel testing community and customers interested in obtaining PSP measurements on a wind tunnel model at the NASA Ames Research Center's Unitary Plan Wind Tunnel. An overview of PSP mechanics, a list of requirements for ones considering PSP measurements, and PSP deliverable details are specified.

I. Introduction

The development of pressure-sensitive paint (PSP) technology spans almost 4 decades. Government agencies and labs, universities, and commercial companies, have collaborated and developed the technology together. The historical background of PSP has an interesting and inspiring beginning, and like most cutting edge technologies, simultaneously in many countries around the world, United States, Germany, Russia, and Japan, had a hand in the early development of the technology[1,2]. Through this collaboration and years of development in the paint's chemical make-up, software development, and advancement in hardware, there are numerous applications and techniques that exploit the chemistry of luminophores, the essence of pressure-sensitive paint. The variety PSP applications across NASA centers present an example of the diversity of applications. At NASA Langley Research Center in Hampton, VA, Watkins, et al.[3] have developed a system for measuring global surface pressure on rotorcraft blades. Watkins's system used a single laser pulse, and data is acquired using the lifetime PSP method. At NASA Glenn Research Center in Cleveland, Ohio, Bencic[4] applies PSP and TSP (temperature-sensitive paint) to scale-model fans. In recent years at NASA Ames Research Center, PSP has been geared towards application in production-style wind tunnels like the Unitary Plan Wind Tunnel 11-by 11-foot Transonic Wind Tunnel and 9-by 7-foot Supersonic Wind Tunnel. The PSP system is deployed as a test-dependent technique per each customer's request.

The pressure-sensitive paint technique implementation at NASA Ames Research Center's Unitary Plan Wind Tunnel, has improved over the past decade. The PSP system has been integrated as part of wind tunnel data system. Through a strong collaboration with the United States Air Force (USAF) for more than fifteen years, NASA and the USAF have collaborated and shared costs to develop a common system. At Arnold Engineering Development Center (AEDC), at Arnold Air Force Base, Tennessee, Sellers[5,6,7] and Ruyten[8] developed a multi-camera, portable PSP system that integrates into a production-style wind tunnel. In 2008, NASA Ames Research Center and AEDC began to collaborate by using the same software developed by Ruyten[9]. The cost and knowledge sharing has proven to be a beneficial investment for both organizations.

A. Introduction

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For each PSP test, up to eight scientific-grade cameras and up to 40 (400-nm wavelength) Light Emitting Diodes (LED) lamps are mounted around the test section. The wind tunnel model is sprayed with the pressure-sensitive paint. The paint contains luminescent molecules that fluoresce when excited by the light source at an intensity proportional to the surface pressure.

NASA Ames uses the 'lifetime' technique to acquire steady-state PSP data. With the 'lifetime' technique, two images are required for each data point, gate 1 and gate 2. Gate 1 image records the paint's luminescence coincident with the light source, while the gate 2 image is taken after the light source has been turned off and measures the luminescent lifetime of the paint. Figure 1 depicts the luminescent response and decay at various pressures.

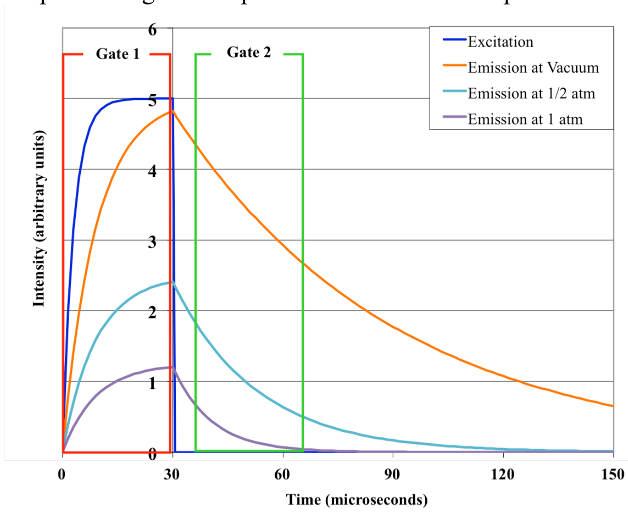

Figure 1. Luminescent Response and Decay versus Time for Varying Pressure

The other standard data reduction approach is the 'intensity' or 'radiometric' technique[10]. With the 'intensity' technique, instead of taking the ratio of two images with wind on, a ratio of a wind-off image to a wind-on image is computed. Comparing the two techniques, the luminescent lifetime approach offers greater immunity to model motion and temperature changes. Each two-exposure data point requires 3-7 seconds depending on the tunnel conditions (Mach, Total Pressure).

The pressure-sensitive paint technique exploits the oxygen sensitivity of luminescent molecules. A luminescent molecule is excited by a high energy photon followed by emission of a lower energy photon. As depicted by the Jablonski diagram[11] in Figure 2, when luminescent molecules are excited to a higher energy state by an energy source and allowed to decay back to the ground state, the time required for the emission intensity to drop by a factor of *e* is the luminescent lifetime[1,10], If the excitation pulse ends at time 0, the emitted intensity at that time is I_0, the emission decays exponentially following the relationship:

$$I = I_0 \, e^{-t/\tau}$$

where *I* is the emitted intensity, *t* is the time and τ is the lifetime.

Materials suspended in an oxygen-permeable binder like the luminescent probe molecule in PSP, are also reaching with oxygen molecules in the air causing the luminescent molecule to be 'quenched' by the oxygen molecules, losing excitation energy, and therefore not emitting as much luminescent energy emitted. Intensity of the PSP emission and local oxygen concentration have an inversely proportional relationship. Higher quantities of oxygen, i.e. higher pressure, result in a lower intensity emitted by the pressure-sensitive paint[7].

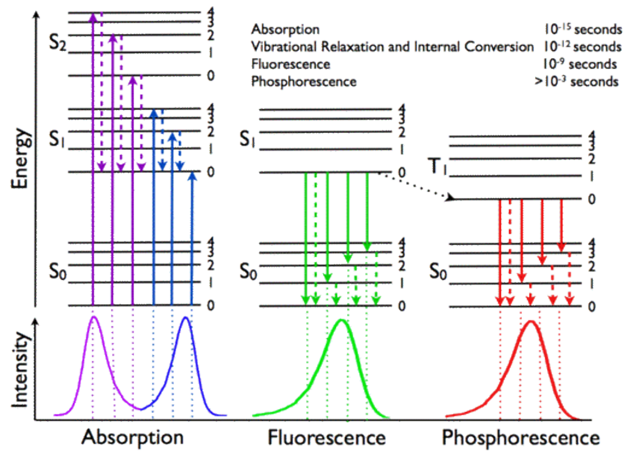

Figure 2. Jablonski Diagram Depicting Excitation and Decay of a Luminescent Molecules

B. Facility

This PSP system discussed in this paper is deployed at NASA Ames Research Center's Unitary Plan Wind Tunnel (UPWT) facility. NASA Ames Research Center's Unitary Plan Wind Tunnel consists of the 11-by 11-foot Transonic Wind Tunnel (TWT) and the 9-by 7-foot Supersonic Wind Tunnel (SWT). The 11-by 11-foot TWT lends itself nicely to optical measurement techniques with multiple windows on each wall of the tunnel. As show in Figures 3 and 4 below, the side walls have a large amount of optical access, and the ceiling and floor wall have several windows allowing viewing access of the whole model. Additional windows have been added to the 11-by 11-foot TWT, as shown in Figure 4, to allow for more optical access and multiple optical techniques to be employed at the same time. More over, research oriented tests, like the capsule wake-deficit study[12], in Figure, or the NASA / Boeing Truss Braced Wing (TBW)[13] test in Figure 4, will exercise as many as 4 optical techniques at the same time. PSP, Infrared (IR) thermography[14], shadowgraph / Schileren, Particle Image Velocimetry (PIV), and model deformation measurements (MDM)[15] are test-dependent systems offered at the UPWT.

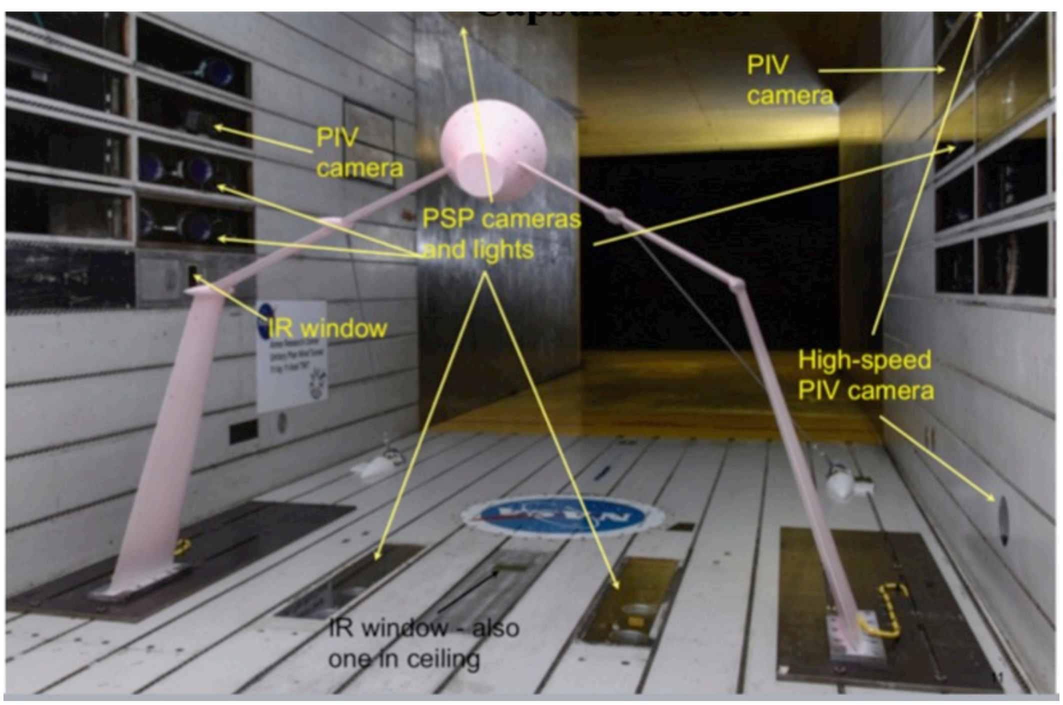

Figure 3. NASA Generic Capsule Model Installed in the 11-by 11-foot Test Section

Figure 4. NASA / Boeing Truss Braced Wing Model Installed in the 11-by 11-foot Test Section

Most customers testing at UPWT and requiring PSP measurements will test at the 11-by 11-foot Transonic Wind Tunnel (TWT)[16,17] This wind tunnel has a Mach number range of 0.2 – 1.4. The Reynolds number may be adjusted by varying the total pressure in the wind tunnel from 0.2 to 2.2 atmospheres. The test section walls are slotted and allows flow into and out of a plenum that surrounds the test section. The 11-by 11-foot TWT test section has windows on each wall of the test section allowing many cameras, lamps, and optical equipment to be mounted in the plenum. Figures 5 and 6 present model drawings of the test section and the location of the rectangular windows with respect to the model location.

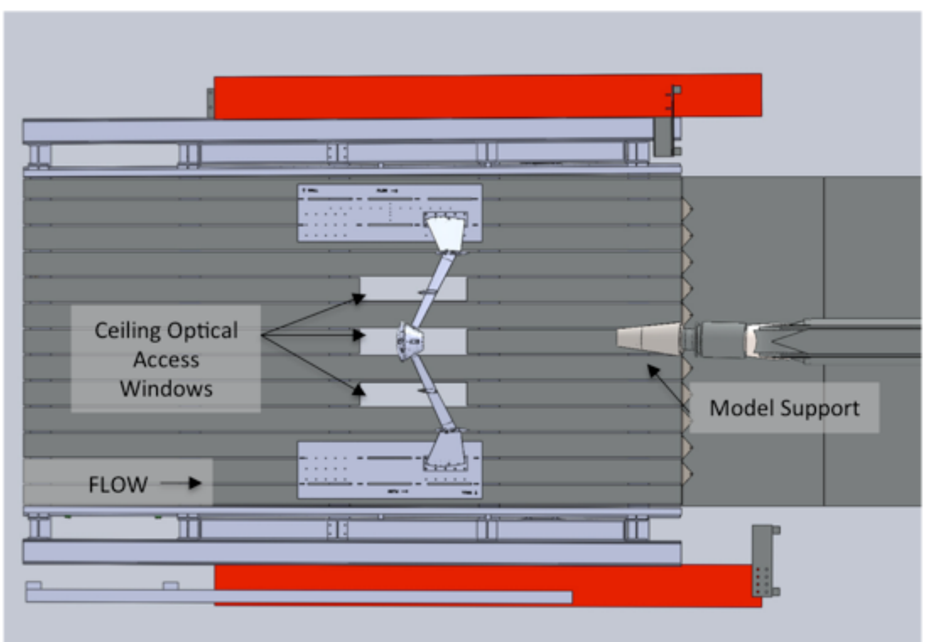

Figure 5. Top View of 11-by 11-foot Transonic Test Section

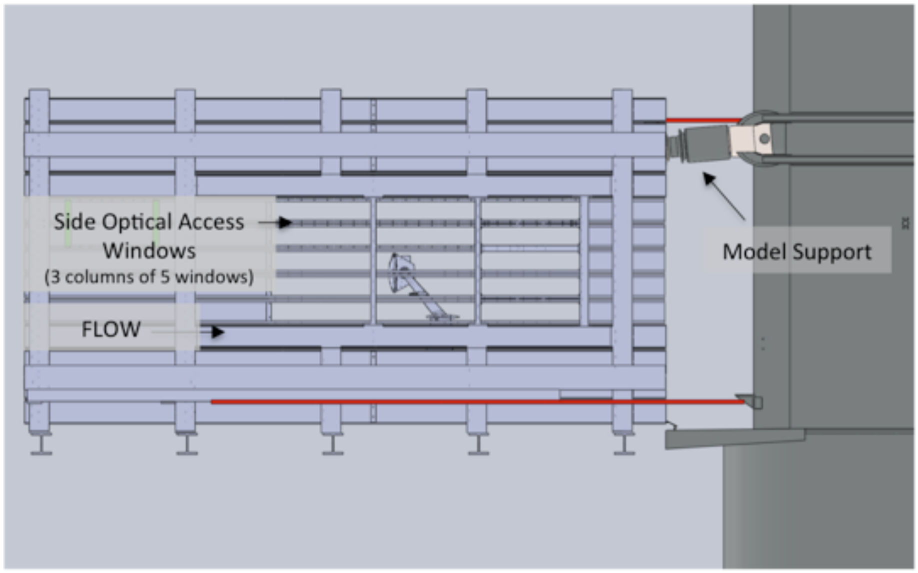

Figure 6. Side View of 11-by 11-foot Transonic Test Section

Optical access at the 9-by-7 SWT is not as ideal as the 11-by 11-foot, however PSP data can still be acquired. Depending on the model size, it can be challenging to compute loads from PSP data since coverage of the model may not be complete, depending on the model and lighting relative to the windows.

II. Wind Tunnel Model and Instrumentation

When a customer is interested in optical measurement data like PSP, several items should be considered: model material, stiffness of sting and balance, duration of data points, and visibility of region of interest. With the increase in optical data, more attention needs to given to the stiffness of the sting and balance. If there are large vibrations, images will be blurry or smeared. Since steady-state PSP is two images taken over several seconds, the ratio of these two blurry images will not compare the same physical location on the model producing a solution with large errors. In addition, since PSP offers a solution to areas that are challenging to instrument with traditional pressure taps, it can often be misleading or present an unachievable solution. PSP is a balance of trade offs, and when designed and implemented correctly can provide a strong, accurate, necessary data set. There are 3 items to consider: PSP can only take measurements on model parts that can be painted, viewed by at least one camera, and ability to excite the paint with energy source (LED lamp). If the camera cannot see a region of interest, then PSP data cannot be accurately acquired.

Figure 7. TBW Model with PSP Installed at 11-by 11-foot Transonic Test Section

Questions for customer to consider are: why is PSP important or useful, and who will be using the PSP data? The answer to these questions will help direct the focus of PSP. There are several problems that PSP can be used to solve. A majority of customers are interested in a global static pressure distribution. This could be used on models that have a range of pressure taps from a dozen to over a hundred in quantity. PSP is used to obtain pressure values on areas that are hard to instrument, like a wing-body junction or a thin airfoil, as seen in Figure 7, or control surfaces - areas that are too thin to instrument with a conventional pressure tap.

Since PSP inherently has high spatial resolution, and the area of the model is well known, the loads experience by components of the model can be computed, however, it is extremely important to know the expectations of computed loads. When a customer is interested in using PSP to compute integrated loads on a control surface, it is important to build the PSP grid and design the instrumentation layout with these areas carefully defined. Full-body integrated PSP loads can be compared to balance loads, however, a few words of caution should be shared. If areas of the model are not viewable to any camera, then loads cannot be computed for that area. In some cases, pressure tap values can be applied to an area for computing the load. Pressure taps are not always in regions with poor viewing angles, however. It is often best to use incremental changes in integrated load between points and rather than overall computed loads.

For extremely complex wind tunnel tests or models, like launch abort simulation tests using high pressure air to simulate abort nozzles and a balance instrumented with delicate bellows, PSP can be used as a backup to the balance. There have been examples of supplementing aero-databases with a blend of PSP and Computational Fluid Dynamics (CFD) data to fill in regions of the database where balance data does not follow the trends of the tests. In these case, careful attention has to be made on what PSP data and what CFD data is used to supplement the database[18].

Lastly when comparing balance loads to PSP computed loads, it is best to compare normal and side forces. Axial forces computed from the balance will contain drag forces due to pressure and shear. PSP only measures the drag due to pressure and does not sense the skin friction.

III. PSP Requirements and Deliverables

A. Pre-Test PSP Requirements

Some customers plan months in advance of their test entry and have well thought out plans for PSP data collection and analysis. Other customers reuse an existing model with a couple dozen pressure taps and delay thinking about PSP until much later in their planning phase. In either case, the first step in planning for PSP tests is simulating the camera views of the wind tunnel model on the actual mounting hardware in the wind tunnel. This exercise aids discussions on what are the priorities when PSP data is collected, where to install PSP cameras, does the PSP installation hamper any other optical equipment or model views, like shadowgraph, what resolution or lens is needed on each camera. Custom software, Vinci, was developed at NASA Ames Research Center by Edward Schairer[19,20]. Vinci is used before each test to virtually model the wind tunnel, wind tunnel model and optical equipment. A low-resolution model, less than 20 MB, stereolithography (.STL) file is preferred. Figures 8 and 9 shows example simulated views for a recent test. Modeling of the lamps and cameras is used to inspect and optimize their locations for best model illumination levels. Since access to the wind tunnel is a limited (and expensive) commodity, advanced planning of the lamp and camera locations and what lenses to use, the physical installation of the equipment is predictable and requires less time. Designing the equipment layout should occur several months before the test is scheduled to run.

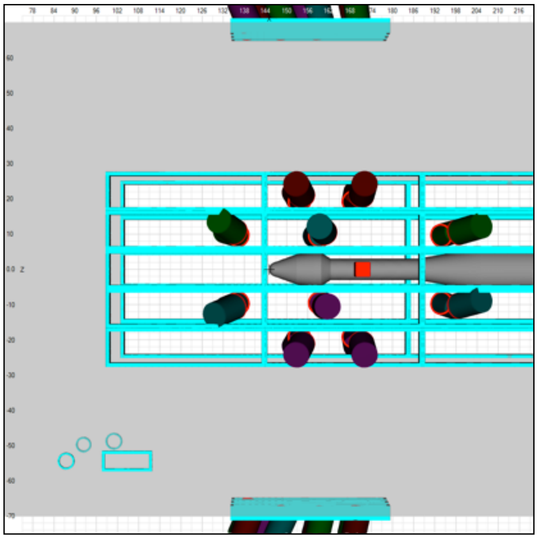

Figure 8. Side View using Vinci

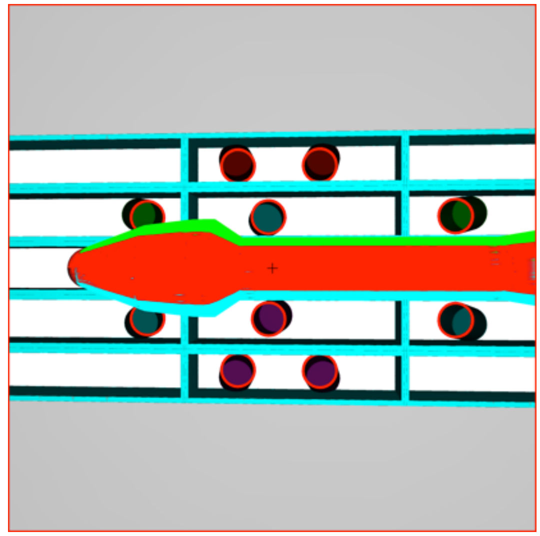

Figure 9. Camera View using Vinci

At least 3 months before the test, a detailed computer-aided drawing (CAD) file of the wind tunnel model needs to be delivered. Having a correct, detailed CAD file is important for clearly defining the regions of interest. For customers requesting PSP-computed loads on controlled surfaces, sections of wings, or vehicle windows, the detailed CAD file must give clear definitions of these boundaries that will be defined as a 'zone'. The final format of the grid is Plot3D, single precision, unstructured, little endian, multiple zone grid with no I-blanks. Generating the grid is the most intensive part of the pre-test process and can take 2 months or more depending on the model complexity. This is the grid onto which the PSP pressures are mapped so it must be carefully prepared well in advance of the test.

One month before the test, the pressure tap co-ordinates should be delivered. The tap locations should be part of the quality assessment report done by the model manufacture after the pressure taps have been installed. The tap pressure measurements are used to anchor the PSP data. An average PSP value at the tap location is computed, and compared with the average pressure tap value. A pressure offset is applied to the PSP data given the deltas between the tap data and PSP data.

B. Painting Requirements

Two weeks before the start of the section, model build-up activities will occur in a model prep rooms. During this two-week window, balance check loads, model build-up, and instrumentation check out will occur. If PSP is a requirement for the test, there will be two stages of painting. First an epoxy primer coat is sprayed onto the model. The PSP adheres better to the epoxy layer better than bare metal. Depending on the model complexity and number of model parts, the process will take 2 – 4 hours. A 12-hour cure is required after the epoxy has been sprayed. The following day, the model will be sanded and prepared for PSP application. Trip dot application is different for each test since trip dot requirements may change. It is most common to apply the trip dots after the epoxy primer layer but before the PSP application.

The PSP application requires two different paints. UPWT purchases paint from Innovative Scientific Solutions, Inc. (ISSI). The first layer is a white base coat consisting of titanium dioxide, which serves as the white pigment, and the proprietary FIB-7 polymer developed by the University of Washington. The base coat provides a uniform white surface, helpful for reflecting excitation light and reducing illumination errors. The white base coat also enhances the PSP emission by reflecting the luminescent emission away from the model surface and towards the camera sensor. The second coat is the active layer or PSP layer. This layer contains the University of Washington proprietary FIB-7 polymer and the luminescent molecule Platinum Tetra Pentafluouophenyl Porphine (PtTFPP) as the probe molecule. PtTFPP is used frequently as pressure sensor because of its high quantum efficiency and low temperature sensitivity[21,22]. The pressure-sensitive paint in reality is an oxygen-sensitive paint since the FIB7 polymer is porous to oxygen molecules, allowing for the interaction of the luminophore, PtTFPP, and the oxygen in the air, which is proportional to pressure. The PSP layers can take 6-10 hours to apply. After the paint has been applied, the paint must be given time to cure. To accelerate the cure time, an oven is constructed around the model, and the model is baked at 140˚F for 4 hours. Once the paint is applied, there is no opportunity to 'touch-up' the paint. The customers must treat the paint with extreme care and caution with the understanding oils and solvents will damage the paint, degrading the data. The total thickness of epoxy plus PSP base and top coat is approximately 1 – 1.5 thousandth of an inch. Approximate roughness is 75-100 microinches.

C. Equipment Installation

The PSP equipment is installed before the model arrives to the test section. The hardware installation is time intensive and requires approximate 30 – 40 hours. The standard equipment installation is 8 cameras and 40 LEDs. The cameras are Roper Scientific CoolSNAP K4 interline transfer cameras with Kodak KAI4040M (2048x2048) CCD sensors operated in accumulation mode[21]. Two cameras are mounted on each wall in an effort to have double coverage of most points on the model. The paint is excited by ISSI's LM4X blue LED (400-nm) lamps. Ten LEDs are installed on each wall in an effort to illuminate the model as uniformly as possible.

D. Calibrations and Data Collection

Once the model has been installed, final pointing angles and focal lengths are set. This process requires the model to be on centerline for approximately four hours. Several calibrations are required once the model is installed and camera focal lengths have been finalized. One calibration is for interior parameters of the camera (focal length, distortion), and the second calibration is for exterior camera parameters[23] (location and orientation in the tunnel). These calibrations are essential in the automation of the processing and must be completed after the model has been installed in the tunnel and before PSP data collection begins.

Before starting the wind tunnel, a final set of calibration images are needed at several different tunnel static tunnel pressures. This set of images is referred to as the 'pump-down' images. If testing below atmosphere, the images are usually acquired at atmosphere, 1600 psf (pounds per square foot), 1200 psf, and 800 psf. If testing above atmosphere, the images are usually acquired at atmosphere, 2400 psf, 2800 psf, and 3200 psf. These images are used to correct for any non-uniformity in paint or lighting. These calibration images need to be collected before coming online after a model change since new parts being installed on the model will have a different response than the parts that have been exposed to the PSP lamps and therefore the paint has not degraded due to lighting. The paint will last for more than two weeks of testing double shifts, but by the end of a two-week, double-shift test, the paint has degraded mostly from model changes.

E. PSP Deliverables

Once online, the goal is have preliminary, processed data available to the customer in near-time. PSP image data are reduced, and a series of calibration are applied to convert the raw intensity values to pressure coefficient (C_p). A complete pressure map of the painted surface is produced for each test condition (data point). PSP data are typically accurate to <1% of tunnel total pressure. The PSP data are provided as a PLOT3D type function file[24] for each data point. Tecplot™ or other P3D viewers are suggested for viewing the PSP data. The grid file typically ends in .grid, and the solution file will be rrrrss.p3d, where r is a four digit run number, zero-padded, and s is a two digit sequence number, zero-padded. For example, Run 105 Sequence 6 would be 010506.p3d. A comma separated variable (.csv) file is also delivered. This file contains the tunnel conditions (Mach, alpha, beta, phi, ect), computed loads from PSP (if desired), and lists Cp of each tap and the PSP C_p value at each tap location. If a customer desires to see the PSP C_p value at certain locations, say along a given chord or along the x-axis of a launch vehicle, 'virtual' taps can be entered, and the PSP Cp value at that x,y,z location will be reported in the data file. There is a csv file for each run and is named r.dat, where r represents the run number.

F. Customer Considerations

When employing pressure-sensitive paint into a wind tunnel test, additional considerations need to be made. First, it is important to reflect on what tunnel conditions are desired and are they the optimal test conditions for PSP. Since PSP response to oxygen, the lower the oxygen content in the air, the less excitation is needed since the luminescent molecule are quenched by the oxygen. If the results are not Reynolds-dependent, it is suggested to run at a lower Reynolds number. If higher Reynolds numbers are necessary, PSP data collection will take 2-5 seconds longer per data point. Second, it is important to understand the model support system at the test facility and consider the alpha, beta range needed for the PSP portion of the test. Like most engineering problems, there is a tradeoff and a compromise must be made between resolution and range of data. The model support system at UPWT has a knuckle-sleeve, meaning the model support is a pitch, yaw system. The model and sting are mounted on the model support strut. The strut can move up and down to compensate for pitching the model in positive or negative alpha, leaving the center of rotation in the center of the tunnel. However, there is no compensation when the model is yawed. This is a detail to keep in mind for optical-based measurements, like PSP. As shown in the figure 9 below, the camera is mounted in the ceiling looking down at the floor. The first image is with the model, a generic launch vehicle[26], at alpha, beta (0,0). The second image is with the model pitched to (-4,0), and the third image is with the model yawed at (0,-4). The images shown below were calibration images taken while calibrating the camera positions. This test was ran at beta = 0. There is very little difference when the model is pitched in the alpha plane, but the model will move out of the field of view when yawed. It is acceptable to yaw the model when testing with PSP, but a lens with a shorter focal length will be installed. It is important to know the alpha, beta range when modeling the wind tunnel model in the wind tunnel using Vinci, as mentioned above. Installing a shorter focal length lens will mean less of the sensor is used per data point. This means lower resolution of actual wind tunnel model area per camera pixel. However, PSP can be used on tests that do yaw the model in beta and produce quality results.

Figure 9a. Model at (0,0) Figure 9b. Model at (-4,0) Figure 9c. Model at (0,-4)

Figure 9. Image of Model Location in Tunnel with various Alpha, Beta Combinations.

G. Safety Considerations

It is important to note the PSP paint requires working with chemicals that are known hazards. Care has been taken to mitigate these hazards for customers and personnel. While applying epoxy and PSP layers, customer and non-essential personnel are removed from location. Personnel applying these layers wear PPE including respirators, coveralls, and hand/eye protection. Considerations for adequate ventilation in the painting locations, such as the 'wall-of-fans' used in the model prep room consisting of 16 boxed fans used to pull air through the room, have been implemented.

The PSP paint hazards are minimal once the model has cured and baked but to protect the paint, the PSP layers should not be touched. During model installation/changes it is imperative to wear gloves to protect the paint from the oils from skin contact. Additionally, it is recommended to follow good industrial hygiene practices such as washing your hands after working with the model.

It should also be noted that the lamps used to excite the paint are UV-A. Under normal test operations, all customers and wind tunnel personnel are excluded from areas surrounding the test section to limit exposure to UV light. Some of the calibrations steps do require personnel to be in the test section while the UV lights are pulsed. For these instances, personnel take care to limit exposure to skin and protect eyes with UV safety glasses.

IV. Reduced Results

To best guide customers on planning PSP test matrix, several tests worth of data have been combined to examine what errors with PSP could be expected. The data below, in Figure 10, shows the absolute average difference between coefficient of pressure (C_P) and the PSP at the same location for various Reynolds numbers.

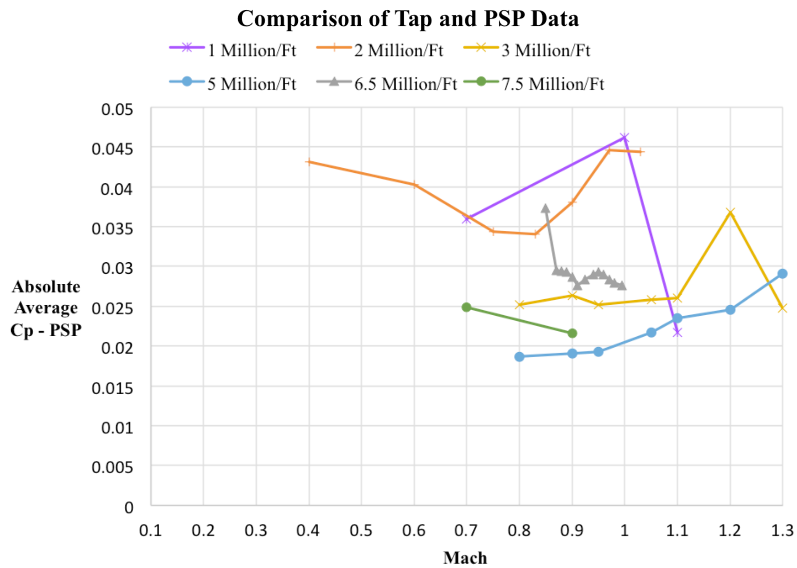

Figure 10. Absolute Average between taps and PSP at same location

Figure 10 shows an average difference between the tap value and the PSP value at the given tap location. Each line represents a different model or configuration for a given Reynolds number. Testing below Mach 0.6, will introduce a larger signal to noise ratio contributing to a larger difference between the tap and the PSP values. At the example above for a Reynolds number of 1 Million/Ft and 3 Million / Foot, there are significant model vibrations at Mach 1.0 and Mach 1.2, respectively, contributing to a larger differences between the tap and PSP values.

V. Future Work

With the increase in interest of optical-based techniques, researchers at NASA Ames Research Center UPWT are developing coatings and techniques to enable PSP, IR thermography, and MDM systems to be deployed and acquire data in parallel. Paint roughness and paint application need to be explored and improved, as well as, improving how final data is reported in the best, coherent way to the customer and combined with wind tunnel balance and pressure data.

The research and advancement of unsteady PSP has gained interest. In November 2015, a test[25,26] investigating the use of unsteady PSP sponsored by the NASA Engineering and Safety Center (NESC) was ran at NASA Ames Research Center's Unitary Plan Wind Tunnel in collaboration with Arnold Engineering Development Center at Arnold Air Force Base, TN. The UPWT is currently developing an unsteady PSP system for production-style wind tunnel testing.

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