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Novel Ground Test Applications of High-Frequency Pressure Sensitive Paint

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Two novel and challenging applications of high-frequency pressure-sensitive paint were attempted for ground testing at Sandia National Labs. Blast tube testing, typically used to assess the response of a system to a hostile blast, was the first application. The paint was tested to show feasibility for supplementing traditional pressure instrumentation in the harsh outdoor environment. The primary challenge was the background illumination from sunlight and time-varying light contamination from the associated explosion. Results showed some low-level exposure to sunlight could be tolerated (early morning testing or intense cloud cover); however, full sunlight swamped the signal from the paint. A separate application of the paint for acoustic testing was also explored to provide the spatial distribution of loading on systems that do not contain pressure instrumentation. In that case, the challenge was the extremely low level of pressure variations that the paint must resolve (120 dB). Initial testing indicated the paint technique merited further development for a larger scale reverberant chamber test with higher loading levels near 140 dB.

I. Introduction

High-frequency pressure-sensitive paint (PSP) is a diagnostic technique for measuring spatially and temporally resolved pressure fluctuations. This diagnostic has been developed over the past twenty years [1, 2] and has now reached a level of maturity that allows the measurement of small pressure fluctuations for wind-tunnel testing applications. For example, the paints have been used to study unsteady cavity flows [3, 4, 5, 6], rotor blade dynamics [7], and turret pressure loading [8], among other aerospace applications.

Other recent novel applications include a two-color paint technique that has have been developed for motion tracking applications [9]. More recent work extends this technique to supersonic free flight projectiles [10]. While these paints used with anodized aluminum models have been able to obtain high-frequency responses for some time, other recent efforts have extended the frequency response of polymer/ceramic pressure sensitive paint as high as 100 kHz [11], while previous limits were closer to 10–20 kHz. This opens up the paint application space to impulsive, short-duration

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testing. For Sandia National Labs, the polymer/ceramic PSP is the paint of choice since it can be non-intrusively applied to the exterior of a system.

In this paper, we explore two novel applications of the high-frequency pressure sensitive paint that push the paint to its capability limits. This includes an outdoor blast tube environment as well as structural acoustic testing. A typical blast tube test characterizes the response of a structure to a hostile blast. To do so, a typical system is instrumented with hundreds of pressure sensors and accelerometers. Despite that dense instrumentation, unsteady pressure loading that occurs, for example on the base of the vehicle, cannot be adequately characterized. Also, for some tests, an actual system is used and in that case, either no pressure instrumentation, or only a few sensors are found on the test article. If developed, the paint would fill in the gaps between pressure sensors and provide a direct measurement of the pressure loading and uniformity of the system under study. However, this is no easy task. The blast tube environment is a short-duration test that requires the newest high-frequency paints. The test also involves explosives, dust, light contamination from the explosion, and sunlight interference if the test is conducted during the day. Even if the test unit is shaded from direct sunlight, outdoor reflections provide strong levels of UV excitation as well as content at the emission wavelength of the paint. The paint must also hold up to sand abrasion, wind, and potential rain.

Another application of the pressure sensitive paints is structural acoustic testing. In these tests, acoustic loading from a bank of speakers is used to excite a system of interest. The excitation can either be periodic or contain broadband frequency content. Typically, the system under test is nonintrusively instrumented with hundred of accelerometers. However, pressure sensors are typically not used as the structure would have to be modified to incorporate them. Instead, the acoustic field is measured with field microphones and inverse methods are used to infer the pressure loading on the system. Application of pressure sensitive paint would allow a non-intrusive, spatially and temporally resolved measurement of the structural loading in such a test in order to verify loading levels and spatial uniformity of the acoustic loading. The challenge for the pressure sensitive paint applications is that the paint needs to be able to resolve very small pressure changes. For the present case, the maximum level was 120 dB which borders the sensitivity limits of the paint.

II. High-Frequency Pressure Sensitive Paint

High-frequency pressure sensitive paint is a diagnostic that uses a luminophore that is quenched by the presence of oxygen and therefore operates as a pressure sensor [1]. A porous base layer is used to create additional surface area that allows the paint to respond quickly - these could be either produced by anodized almunim, or by the application of a porous coating to a model. The luminophore must be excited over a specific wavelength at which it absorbs the incident light and must emit at a separate wavelength. A filter on the imaging camera is used to eliminate excitation light and capture only the paint emission which is then calibrated to pressure.

The high-frequency pressure-sensitive paint used for the blast tube test was a formulation recently presented by

Ref. [11]. The recommended paint formulation has a response time of approximately 100 kHz, a pressure sensitivity of 0.85%/kPa, and less temperature sensitivity than other commonly used high-frequency paints (≈ 1% per deg C). Each of these is important for the blast tube test which involves an impulsive test with large temperature gradients. The formulation used in the present paper was a mixture of RTV, 80% weight of BN (Boron Nitride), Toluene, and a Ruthenium based pressure-sensitive luminophore: Tris(4,7-diphenyl-1,10-phenanthroline) ruthenium(II) dichloride (Ru(dpp)3). This BN particle does not have as desirable characteristics as that of m-silica (its pressure sensitivity is slightly lower and only 0.62% per kPa), but the lead time for obtaining the m-silica prevented its use for these tests.

For the acoustic test, since the desired frequency response was lower and there were no expected temperature changes, high-frequency pressure sensitive paint from Innovative Scientific Solutions, Inc. (ISSI) was also tested. This paint uses a platinum-tetra-fluoro-phenyl-porphyrin (PtTFPP) luminophore that is sprayed on top of a porous ceramic binder. This formulation has a frequency response greater than 10 kHz, a pressure sensitivity of 0.6% per kPa, and a temperature sensitivity of 3.6% per deg C [12]. No temperature change was expected for the test, and frequencies of acoustic excitation were limited to approximately 2 kHz, making this paint a good choice for acoustic testing.

III. Blast Tube Test Setup and Results

The blast tube test was conducted in Sandia's 120 ft blast tube facility. Figure 1(a) shows a picture of the setup. The white tube is the blast tube itself. Explosive charges are hung at the far end and are detonated. The explosion creates a shock wave that travels through the tube, generating a planar shock wave that impinges on a system. Although a typical system is hung at the center of the blast tube and dropped as the shock impacts the unit, for this test, the system was simply placed on the ground near the blast tube. This setup was simpler and provided ease of access, while also allowing the demonstration of the PSP technique. Charges from 5 to 15 pounds were used for this test series to generate pressure loading on the system up to 10 psi. A typical test could have charges in excess of 40 lbs. Future blast tube tests are planned to mature the paint setup to withstand the higher blast levels.

For these tests, only the nosetip of a typical system was painted (Fig. 1(b)). This provided adequate coverage to compare with nine Endevco 8530B-500-120M9 pressure transducers within the field of view. Four 460-nm water-cooled LED lights with collimators (Fig. 1(c)), model LM2XX-DM-460 from Innovative Scientific Solutions Incorporated (ISSI) were used to excite the paint. These lights were protected from the blast by a bunker and sand bags. The bunker was placed 2 feet away from the model it was illuminating. UV transmissive Plexiglas was used as the window of the bunker in order to pass as much of the excitation light as possible. This window was cleaned between tests to remove dust that was stirred up by the explosion.

To the left of the blast tube, a large job box (Figure 1(d)) contained the UV light control boxes, a water chiller, and other associated electronics to run the lights. This job box was modified to incorporate ventilation and fans to attempt to keep the internal electronics cool. Additionally, heat-reflecting air bubble insulation sheets were placed around the job box to repel external heat. Despite both cooling efforts, during some mid-day testing when the temperature reached near 80 F, the LED light water chiller did begin to overheat. As a result, a shade structure was setup over the job box in between runs and the job box was opened and allowed to cool.

Yet another bunker (Fig. 1(a)), 17 feet from the model, housed a high-speed Phantom v2512 camera with a 400-mm lens at f2.8. This camera acquired high-speed images of the model at a framing rate of 25 kHz with a 1280 x 800 resolution. A 625 nm, 50 nm bandpass filter was used to capture the paint emission and eliminate as much sunlight interference as possible. Both the lights and camera were remotely operated.

Fig. 1 Blast tube test setup. (a) Overall view of blast tube; (b) System with shade structure and nosetip cover; (c) UV light setup; (d) Job box.

Because the paint photodegrades with time, a wooden cover for the nosetip was constructed (Fig. 1(b)). This was removed approximately 10 minutes before the tests were conducted just before explosive charges were hung and then replaced approximately 10 minutes after a test after the all-clear was given. The model was additionally shaded from direct sunlight with a shade structure and tarp for all tests without cloud cover. The hope was that this tarp would help reduce paint degradation and also reduce sunlight interference at the paint emission wavelength. Unfortunately, background reflections still exposed the model to significant UV contamination, even with the tarp in place. The tarp/shading technique will not be used for future tests.

A total of eight tests were conducted over two days. The first day varied the strength of the explosive charge from 5 to 10 lbs to make sure that the equipment and paint could hold up to the harsh outdoor blast environment. All equipment and paint survived. For the first day tests, the model was shaded from direct sunlight by a tarp, and the paint layer was recoated following the fourth run.

On the second day, an early morning test was conducted to test the paint with as little sunlight exposure as possible. This test was conducted just before sunrise. The second and third runs were under extensive cloud cover but increasing sunlight. The fourth run was again under full sunlight exposure with a tarp over the model. Some of the second day runs used 15 lbs of explosives to generate higher loading levels on the system. Table 1 lists the parameters and weather for each run.

Table 1 Blast Tube Test Conditions

Test	Charge Weight (lbs)	Model Tarped	Temperature (F)	Pressure (psia)	Humidity (%)
1	5	yes	80.7	12.22	39
2	5	yes	82.9	12.22	34
3	10	yes	85.4	12.21	32
4	10	yes	88.3	12.19	26
5	10	no	64	12.25	81
6	15	no	64.2	12.25	83
7	10	no	66.5	12.25	67
8	15	yes	69.2	12.25	61

Test five (conducted before sunrise) provided the best data and indicated that the paint technique is promising for further development at the blast tube. Figure 2 shows several images from the high-speed PSP video. Pressure sensors show up as blue circles in the images. Figures 2(a) and 2(b) show the incident shock wave moving downstream of the nosetip, while Figure 2(c) and 2(d) show a reflected shock wave moving upstream. Although the images are noisy because of the challenging setup, the incident and reflected shock waves can be clearly seen. Other narrow diagonal lines seen in the images are a result of camera noise.

Figure 3(a) shows a comparison of pressure traces from the paint and a pressure sensor just beside it. Paint data cannot be acquired after approximately 0.08 s because dust and dirt that is stirred up by the blast begins to obscure the field of view. However, the important part of the test is over by that time. This comparison takes into account the pre-shot lighting condition, as well as an estimate of the time-varying light generated by the explosion itself. The paint provides a good representation of the incident shock and as well as a reflected shock. However, there are noticeable discrepancies between the two measurements. The peak pressure measured by the paint is too low, and noise levels from the paint are also higher. The frequency response of the paint is also lower than pressure sensor, which may contribute to the peak pressure discrepancy.

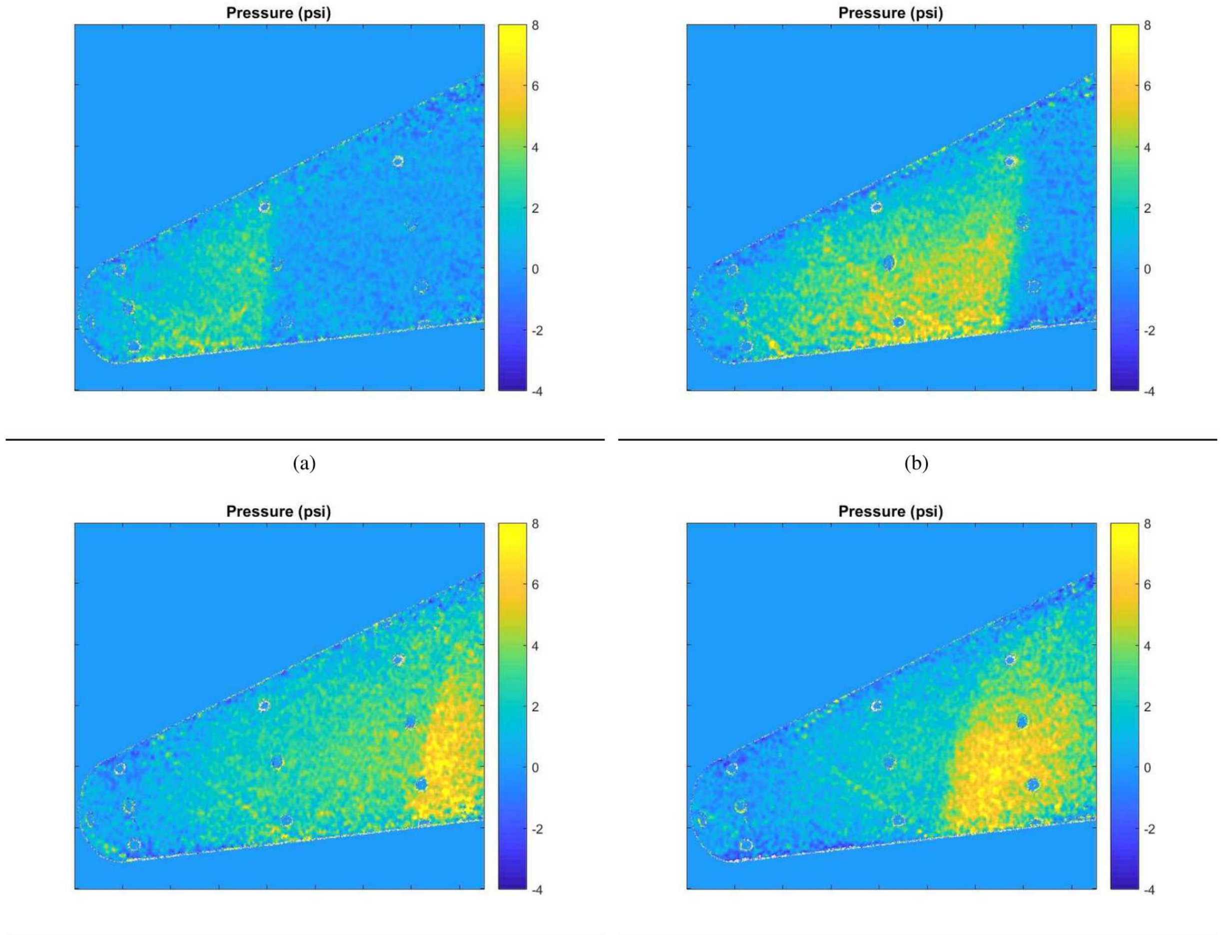
Figure 4 shows the time varying image intensity of the explosion, as captured by the camera. This image intensity decays rapidly with time during the PSP dataset. The mean is subtracted from the this value at the reference image time of the PSP computation, just before the incident shock reaches the system. This value is then subtracted out when computed the intensity ratio used for pressure computation:

$$\frac{Iref}{I} = \frac{I_{ref} - I_{pretest}}{I - I_{pretest} - I_{explosion}} \tag{1}$$

The image intensity from the explosion was measured at a point on the nosetip that was not painted. For future tests, a portion of the model should be painted without the luminophore mixed in to provide a more accurate measure of the time varying light intensity seen by the model. Figure 3(b) shows the raw data without taking into account this time-varying light source. The trend is incorrect and over predicts the pressure change as the explosion light intensity decreases. If the time-varying light intensity is subtracted out, the correct qualitative trend can be matched.

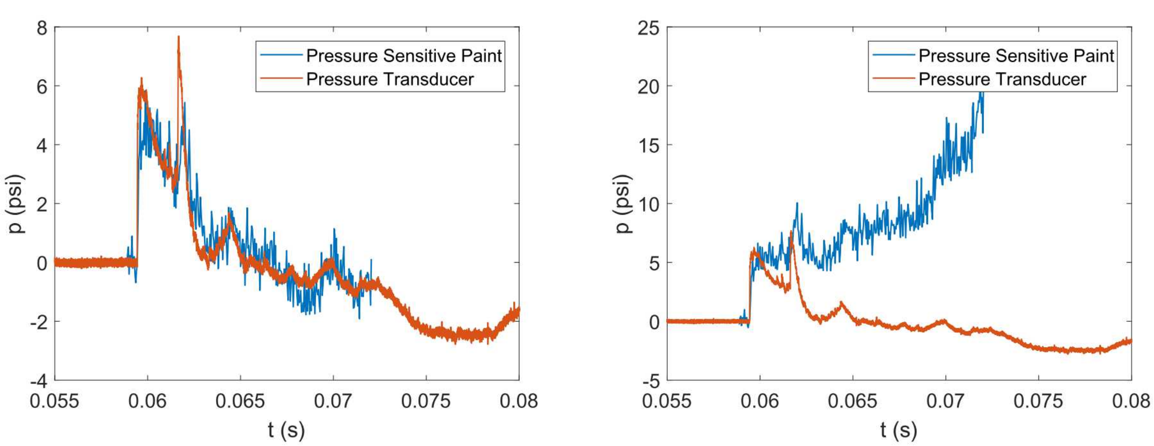
Figure 5(a) and 5(b) show time traces for other runs that also contained sunlight interference. Test 6 was with intense cloud cover and test 3 was a run in full sunlight where a tarp was used to shield the model. As more and more sunlight exposure occurs, the sensitivity of the measurement is decreased because the light contamination saturates the images. As a result, measurement noise increases significantly. To better correct for this degradation of sensitivity, an in situ static calibration with the same light contamination as the run would be needed to properly capture the effects of the light saturation. This correction, however, would not eliminate the inherent noise in the system from the background light illumination.

Future blast tube tests will take into account the lessons learned from this initial round of tests. Testing will be conducted in the dark, either after sunset or just before sunrise. A portion of the model will be painted without the luminophore to track the light intensity generated by the explosion, without an accompanying intensity change due to pressure. This will allow a more quantitative correction for the time-varying light intensity. This could also be done with a two-color paint where one luminophore is insensitive to pressure and would only be used to measure the luminosity from the explosion. Finally, work will focus on maturing the setup to withstand higher charge levels of 40 lbs and above. Future setups will image a system hung at the center of the blast tube and should incorporate a two-color paint system to track the model as it is released and impacted by the impinging shock.



(a) (b) (c) (d)

Fig. 2 Snapshots of blast tube PSP results. Flow is from left to right. (a-b) Incident shock; (c-d) Reflected shock.



(a) (b)

Fig. 3 Blast tube PSP results (a) Time trace comparison with explosion light intensity corrections; (b) Time trace comparison without explosion light intensity corrections.

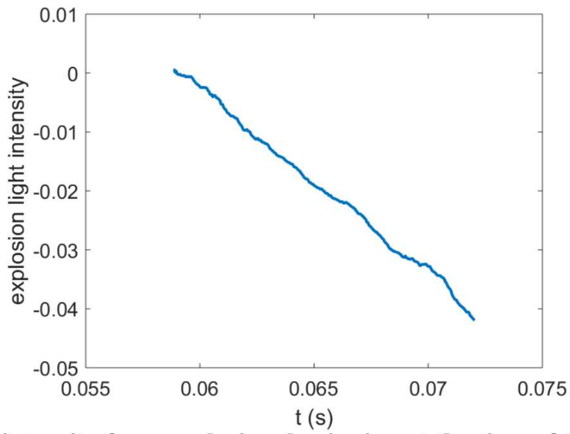
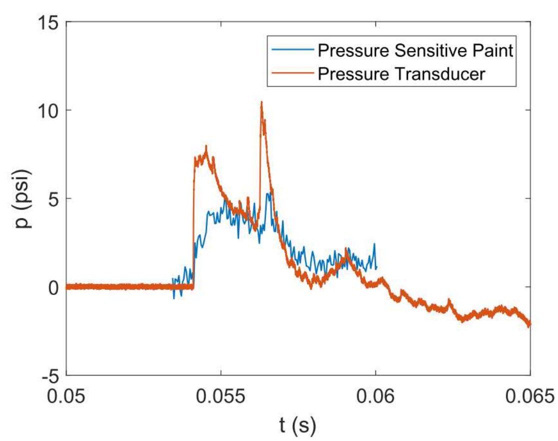
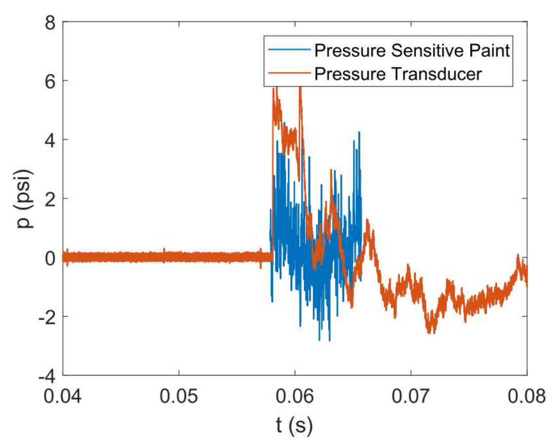


Fig. 4 Time-varying image intensity from explosion, beginning at the time of the PSP reference image. Initial mean value is removed.



(a)



(b)

Fig. 5 Blast tube PSP results with additional background illumination from sunlight (a) Test 6 under cloud cover (b) Test 3 under tarp but full sunlight.

IV. Acoustic Test Setup and Preliminary Results

Acoustic testing is used to study structural response to flight-like acoustic loading. Typical tests instrument a system with hundred of accelerometers, but not surface pressure instrumentation. Instead, the acoustic field is measured with an array of field microphones and the surface pressure loading is calculated using inverse methods. However, it is desired to verify the surface pressure computed with the inverse methods, and also verify the uniformity of the loading generated in the acoustic test.

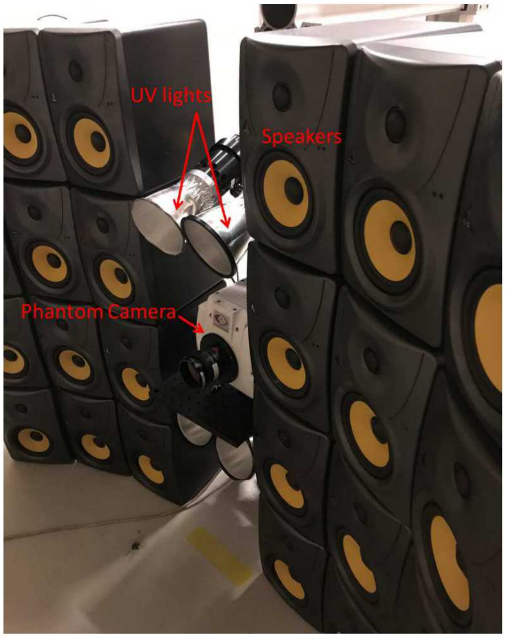
Typical tests in a reverberant chamber can reach levels up to 140 dB. However, for this scoping study, the acoustic test was conducted in a lab scale setting. Twenty-four speakers linked to a control system (Fig. 6(a)) were used to generate an acoustic field on a 1 ft by 1 ft painted area of a flat plate (Fig. 6(b)). Either random or sinusoidal signals (up to 2 kHz) could be generated with levels up to 120 dB. This pressure loading is 10 times lower than might be obtained in the reverberant chamber, so an already challenging setup is further limited by the lab scale test. However, if the paint appears to offer a viable measurement technique at 120 dB, it will certainly be useful when loading levels reach 140 dB.

Both surface-mounted and field microphones were used to characterize the loading of the plate. Kulite Mic-062 pressure sensors were placed at four locations on the plate, to provide direct comparisons to the pressure-sensitive paint. Six PCB130B40 surface mount microphones were also used around the periphery of the plate. Finally, 6 PCB130A23 field array microphones were used to characterize the acoustic field around the plate.

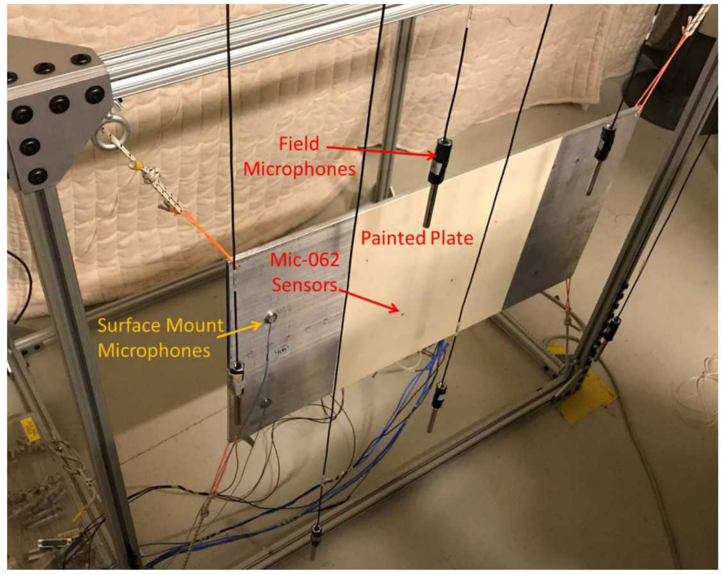
The entire setup was in a tented structure lined with acoustic absorption material. The same UV lights and camera as the blast tube setup were used. A 50-mm lens with a 550-nm high-pass filter was used with the Phantom 2512 camera. Images were acquired with a 1280×800 pixel resolution at 12 kHz. Remote operation of the speakers, lights, and cameras was conducted outside the tent.

Sixteen runs were acquired during the acoustic testing. Each run varied the speaker input from random broadband excitation, through sine-wave excitation at 500, 1000, and 2000 Hz. These different inputs should generate distinct spatial patterns on the plate. Peak levels near 125 dB were obtained for some of the 500 Hz sine wave runs, while higher frequency sine-wave excitation reduced the peak levels to closer to 115 dB. Two types of high-frequency PSP were tested including the Egami paint formulation [11] used in the blast tube test as well as the ISSI high-frequency PSP [12]. The Egami paint formulation was used on the full acoustic test plate, while the ISSI paint was applied to a small uninstrumented plate and tested in later runs. For the ISSI paint tests, plywood was used to line the inside of the tent in an attempt to increase the decibel level. Comparison between field microphones indicated a 2-3 fold increase in acoustic loading for the ISSI paint tests in comparison to the Egami paint formulation.

Unfortunately, the Egami paint formulation only produced a slight paint signal above the background noise. Figure 7(a) shows a comparison of the power spectral density from the paint (average of a 15 x 15 pixel square) and an adjacent Kulite pressure transducer for runs with 500, 1000, and 2000 Hz sine excitation as well as broadband excitation. It



(a)



(b)

Fig. 6 Acoustic test setup. (a) Speakers, UV lights, and camera setup (b) Painted plate and microphone instrumentation.

appears that the paint may be resolving the 500 Hz signal, though the amplitude is incorrect for unknown reasons. A slight peak appears in the 1000 Hz case, though it is barely discernible above the noise level. As discussed above, the peak excitation level for the higher frequency cases was near 114 dB as opposed to 124 dB in the case of the 500 Hz excitation. Both the 2000 Hz sine and broadband excitation levels are below the paint noise floor.

Figure 7(b) shows a similar comparison for the ISSI paint. This paint formulation clearly shows periodic sine excitation for the 500, 1000, and 2000 Hz cases; therefore, this paint appeared to have a better signal-to-noise ratio than the Egami paint formulation, even though the quoted sensitivities of both paint formulations were the same. It is unclear if there was an issue with the application of the Egami paint or if the difference is due to some other reason. Direct comparisons between the paint formulations are difficult since higher amplitudes near 120 dB were generated for the later ISSI paint tests because plywood was used to line the inside of the acoustic testing tent to enhance reverberation.

Unfortunately, Kulite microphones were not installed in the ISSI paint test plate. However, an indirect comparison of pressure traces from the PSP and field microphone was conducted. Figure 7(c) shows time traces from the two field microphone and the PSP which both show a periodic sine signal. However, the PSP has additional low-frequency content in the time traces for unknown reasons. The ISSI paint test plate was also much smaller than the large plate implemented for the Egami paint formulation. As a result, spatial wavelengths associated with the acoustic test could not be resolved with the ISSI paint test. Future tests will implement this paint on a larger plate with simultaneous surface pressure instrumentation.

Although the SNR of the PSP was marginal for these tests, the results do show that pressure-sensitive paint is a viable diagnostic for acoustic testing. Follow-on testing will be conducted in a reverberant chamber that can reach 140 dB. This will provide a signal-to-noise ratio much higher than the present test and it is hoped that the spatial structure of the acoustic loading will be able to be resolved with the PSP.

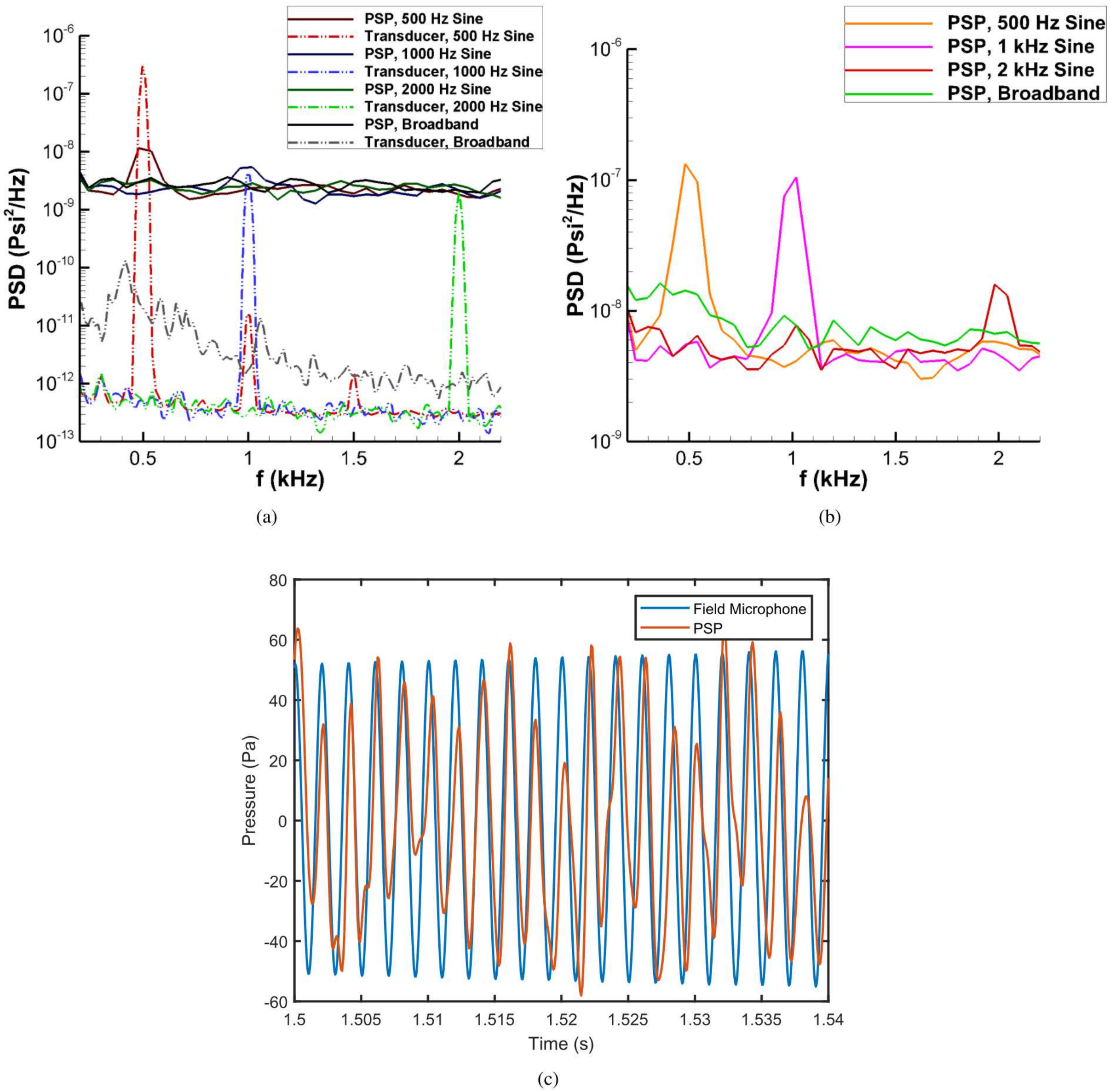


Fig. 7 Preliminary acoustic test results. (a) Power spectral density comparison between the paint and a pressure transducer, Egami paint formulation; (b) Power spectral density for ISSI paint formulation; (c) Pressure trace comparison between paint and a field microphone.

V. Concluding Remarks

Two novel ground-test applications of high-frequency pressure-sensitive paint were tested at Sandia National Labs. In both cases, the paint provides spatial information on the loading of a structure without the need to install hundreds of pressure sensors. This is especially useful in applications with asymmetric, high frequency pressure loading, or on systems that cannot be modified to incorporate pressure sensors.

The first application explored use in an outdoor blast-tube test. Good agreement between the paint and in-situ pressure sensors was obtained, showing promise for using this diagnostic as a routine part of blast-tube testing. The paint was able to withstand the harsh outdoor environment. Testing indicated that to obtain adequate signal-to-noise ratios, the test must be conducted at night or under intense cloud cover. This avoided camera saturation and loss of sensitivity from sunlight interference. Also, the time-varying light intensity from the explosion at the opposite end of the tube must be accounted for to properly compute the pressure loading on the model. Future tests may incorporate a two-color paint scheme where one luminophore is insensitive to pressure in order to provide a measurement of the background signal. An alternative is to measure the light intensity with a photodiode or also paint a portion of the vehicle without the pressure-sensitive luminophore to properly account for the time-varying light intensity.

Acoustic testing was also explored as another application of the pressure-sensitive paint. For the present setup, only levels of 120 dB could be reached, which provided a minimally acceptable signal-to-noise ratio with the paint. Despite this noise level, reasonable data were obtained and indicated that the paint is a viable diagnostic for an acoustic test. Future acoustic tests will be performed in a reverberant chamber where levels of up to 140 dB should provide much better signal-to-noise ratios and allow resolution of the spatial distribution of the acoustic loading on a system.

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