Pressure-sensitive paint as a distributed optical microphone array

James W. Gregoryb) and John P. Sullivan
School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907

Sameh S. Wani and Narayanan M. Komarath
School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332

(Received 1 June 2005; revised 27 October 2005; accepted 31 October 2005)

Pressure-sensitive paint is presented and evaluated in this article as a quantitative technique for measurement of acoustic pressure fluctuations. This work is the culmination of advances in paint technology which enable unsteady measurements of fluctuations over 10 kHz at pressure levels as low as 125 dB. Pressure-sensitive paint may be thought of as a nano-scale array of optical microphones with a spatial resolution limited primarily by the resolution of the imaging device. Thus, pressure-sensitive paint is a powerful tool for making high-amplitude sound pressure measurements. In this work, the paint was used to record ensemble-averaged, time-resolved, quantitative measurements of two-dimensional mode shapes in an acoustic resonance cavity. A wall-mounted speaker generated nonlinear, standing acoustic waves in a rigid enclosure measuring 216 mm wide, 169 mm high, and 102 mm deep. The paint recorded the acoustic surface pressures of the (1,1,0) mode shape at \( \sim 1.3 \) kHz and a sound pressure level of 145.4 dB. Results from the paint are compared with data from a Kulite pressure transducer, and with linear acoustic theory. The paint may be used as a diagnostic technique for ultrasonic tests where high spatial resolution is essential, or in nonlinear acoustic applications such as shock tubes. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2140935]

PACS number(s): 43.38.Zp, 43.25.Zx, 43.25.Gf, 43.20.Ks [AJZ]

Pages: 251–261

I. INTRODUCTION

Optical microphones are transducers that modulate light in response to acoustic signals. Most prior instances of optical microphone designs involve the use of some mechanical membrane to modulate the light. Bilaniuk\(^1\) has classified optical microphone transduction techniques into three categories—intensity modulating,\(^2,3\) polarization modulating,\(^4\) and phase modulating.\(^5\) Often these optical microphones are interrogated through fiber optics. The primary advantage of this type of setup is that electrical connections are not required, allowing optical microphones to be used in harsh experimental environments. There are some drawbacks to this type of microphone, however. The typical sensitivity of these optical transducers is not as good as traditional microphones. Furthermore, the fiber-optic interrogation bundle must be positioned close to the sensing membrane element, and these devices are limited to point measurements.

Pressure-sensitive paint (PSP) is detailed in this article as an alternative form of optical microphone. The paint is similar to optical microphones in that it modulates light intensity in response to an acoustic signal. It is fundamentally different, however, in that the paint does not have any mechanical membranes or moving parts. Instead, pressure-sensitive paint modulates the light intensity through a repeatable chemical interaction of the sensing layer with atmospheric oxygen. A photodetector such as a CCD camera or photomultiplier tube (PMT) is employed for interrogation of the paint. Since the paint is composed of nano-scale chemical sensors, the microphone spatial density is quite high. Thus, pressure-sensitive paint serves as a nano-distributed optical microphone array with a spatial resolution limited only by the pixel resolution of the photodetector. The high spatial resolution and fast response allows the paint to be used for high-frequency applications where the characteristic wavelengths are small.

McGraw et al.\(^5\) recently demonstrated pressure-sensitive paint as a form of optical microphone. They calibrated the paint for intensity and frequency response, and measured acoustic pressure fluctuations in a standing-wave tube. McGraw’s paint formulation involved a chemical sensor of platinum tetra(pentafluorophenyl)porphine (PtTFPP) mixed with a polymer and applied to thin-layer chromatography plate. With this formulation they resolved pressure fluctuations as low as 6 Pa in a frequency range of 150–1300 Hz. Their measurements, however, were limited to the end plate of a one-dimensional standing wave tube where light intensity was integrated over a large area. By integrating light over a large area they were able to improve the signal-to-noise ratio of their measurements, but sacrificed the ability to make two-dimensional measurements. One of the characteristic advantages of pressure-sensitive paint is the ability to make two-dimensional measurements with high spatial resolution. Sakaue has also demonstrated acoustic measurements with pressure-sensitive paint.\(^6\) He developed a paint formu-

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\(^{a)}\) A small portion of this work was presented in “Fluidic Oscillator as a Dynamic Calibration Tool,” at the 22nd AIAA Aerodynamic Measurement Technology & Ground Testing Conference, St. Louis, MO, June 2002.

\(^{b)}\) Electronic mail: jim.gregory@alumni.purdue.edu
lation incorporating PtTFPP deposited on an anodized aluminum surface. Sakaue’s measurements were also in a one-dimensional standing wave tube, although the PSP was positioned along the length of the tube. His data were recorded at very acoustic high pressures, on the order of 172 dB.

When used as a distributed optical microphone array, pressure-sensitive paint can provide quantitative mode-shape visualization data. Previous methods for determining acoustic mode shapes have been either qualitative or quantitative methods. Galaitsis developed a qualitative visualization method based on the refraction of light through water.7 His experiments involved a rectangular cavity partially filled with water. The standing waves inside the cavity deformed the water such that a time-averaged image of the mode shape could be recorded by the varying refraction of light passing through the water. Chinnery et al. have recently employed schlieren imaging techniques for the visualization of mode shapes in cylindrical cavities at ultrasonic frequencies.3

Quantitative methods for determining mode shapes have required microphone measurements. Either a large array of microphones is required, or more commonly, a small array that can be traversed throughout the region of interest. Smith suggested the use of microphone measurements at multiple locations within an enclosure.9 He computed the transfer function between signals from multiple microphones at different locations in order to determine the mode shape. Nieter and Singh developed a concept whereby the transfer function between a driving speaker and multiple microphone measurements was used to calculate the mode shape.10 Their experiments used a traversing microphone within a cylindrical resonance cavity, with the results showing good agreement with linear acoustic theory. In subsequent work, Kung and Singh determined mode shapes in three-dimensional cavities through microphone measurements on the cavity boundary.11

Knittel and Oswald,12 as well as Whear and Morrey,13 developed a technique using an array of two or three microphones to calculate a time-resolved spatial derivative of pressure. They coupled this information with accelerometer data for the loudspeaker cone to determine the mode shapes using structural modal analysis software.

In the current work a rigid, rectangular cavity excited by a single-frequency sound source was chosen as a benchmark application for evaluating the capabilities of PSP for acoustics measurements. The advantage of the rectangular enclosure is that the pressure field is well-known from linear acoustic theory.14 Furthermore, high-amplitude pressure waves may be generated through resonant amplification, enabling the use of a relatively low-power compression driver to generate measurable pressures. The cavity used in this work was originally developed and used for acoustic shaping experiments in microgravity, where acoustic radiation forces were used to collect particles into desired surfaces.15

Theoretical16 and numerical17 solutions are available for high-amplitude, nonlinear wall pressures in resonant enclosures, but an experimental technique specific to this cavity is needed. Thus, pressure-sensitive paint was used to verify the surface pressure distribution in a rigid enclosure.

II. PAINT DEVELOPMENT

A. Characteristics of pressure-sensitive paint

Pressure-sensitive paint is an oxygen-sensitive optical measurement technique, traditionally developed for aerodynamics applications.18,19 The oxygen-sensing molecule, known as the luminophore, interacts with oxygen atoms in the test gas in a reversible process that alters the luminescent intensity of the paint. According to Henry’s law, the oxygen concentration within the paint layer is proportional to the local partial pressure of oxygen, which is proportional to absolute pressure of air. Thus, the oxygen sensor forms the basis for a pressure-sensitive paint.

In a typical pressure-sensitive paint test, the luminophore molecules are excited to a heightened energy state by illuminating the paint with light of a specific wavelength. This light is best tuned to the absorption spectrum of the paint, and is typically in the ultraviolet to blue range of the spectrum. Before excitation, electrons of the luminophore molecule are in the ground state. When the paint is illuminated, photons are absorbed by the luminophore molecules and the luminophore electrons are elevated to a heightened vibrational state. These electrons in the higher state can release their energy through several mechanisms which return the energy of the molecule back to its ground state. For pressure-sensitive paint applications, the relevant and dominant energy transfer mechanisms are oxygen quenching, phosphorescence, and radiationless decay. For quasisteady quenching, these mechanisms are denoted by the rate constants $k_q$, $k_p$, and $k_{NR}$, respectively. Oxygen quenching occurs when oxygen molecules in the test gas collide with the activated luminophore molecules. An energy transfer occurs from the luminophore to the oxygen, as the oxygen is easily elevated to a heightened energy state. The oxygen molecules subsequently release this energy through long-wavelength infrared radiation or vibrational relaxation. Phosphorescence of the luminophore (also referred to as luminescence) is the radiative release of energy at a longer wavelength than the excitation light. Nonradiative transfer of energy involves an intersystem transfer from the triplet state to the singlet state, and subsequent vibrational relaxation. Thus, the primary physical mechanisms of energy transfer of interest in pressure-sensitive paint applications are phosphorescence and oxygen quenching. Oxygen quenching is related to the local acoustic pressure, while phosphorescence is measured by photodetectors.

The rate of phosphorescent emission of a pressure-sensitive paint ($I$) may be expressed as a first-order differential equation:18

$$\tau \frac{dI}{dt} + I = \tau k_p \Phi_T a(t), \quad (1)$$

where $\Phi_T$ is the triplet quantum yield (the fraction of absorbed photons that produces luminophore molecules in the triplet excited state), and $a(t)$ is the photon absorption rate. The development of Eq. (1) assumes that the lifetime of the luminescent decay is much faster than the characteristic time scale of the pressure fluctuations, which is valid for the sub-
ject acoustics application. The luminescent lifetime $\tau$ is given by

$$\tau = \frac{1}{k_{\text{NR}} + k_p + k_Q},$$

(2)

and the quenching constant is related to the local oxygen concentration $[O_2]$ by

$$k_Q = \kappa_Q[O_2],$$

(3)

where $\kappa_Q$ is the quenching rate constant. Thus, the quasi-steady form of Eq. (1) is given by

$$I = \pi k_p \Phi_T d = \frac{k_p \Phi_T d}{k_{\text{NR}} + k_p + \kappa_Q[O_2]}.$$  

(4)

An intensity ratio may be obtained when Eq. (4) is expressed as a ratio between the test condition and vacuum conditions (the complete absence of oxygen):

$$I_0 \frac{I}{I_0} = \frac{k_{\text{NR}} + k_p + \kappa_Q[O_2]}{k_{\text{NR}} + k_p} = 1 + K_{\text{SV}}[O_2].$$  

(5)

Here the subscript 0 indicates vacuum conditions, and $K_{\text{SV}}$ is the Stern-Volmer constant. Equation (5) expresses the essence of the pressure-sensitive paint technique: measured light intensity from the paint is inversely proportional to the oxygen concentration.

In practical applications it is often infeasible to use vacuum as a reference condition ($I_0$). Thus, an arbitrary reference condition ($I_{\text{ref}}$) is often used by taking the ratio of Eq. (5) at the test condition and a practical reference point such as atmospheric conditions. This yields the Stern-Volmer relation,

$$I_{\text{ref}} \frac{I}{I_{\text{ref}}} = A + B \frac{P}{P_{\text{ref}}},$$

(6)

which is common in aerodynamic applications of pressure-sensitive paint. Here the oxygen concentration $[O_2]$ has been replaced by pressure $P$ since local oxygen concentration varies with air pressure. $A$ and $B$ are the Stern-Volmer calibration coefficients, which are typically sensitive to temperature.

B. Morphology

Conventional pressure-sensitive paint formulations are composed of oxygen-sensitive luminophore molecules embedded in a polymer matrix. The polymer serves as a mechanical binder to hold the luminophore to the model of interest. The properties of most polymers inhibit the diffusion of oxygen within the binder and delay quenching of the luminophore. Sakaue et al. have shown that the response time of conventional paint formulations can be as long as a few seconds. These slow response characteristics preclude the use of traditional paint formulations for acoustic measurements. Therefore, a new morphology has been developed to enable rapid response times.

The time response of paint formulations may be modeled by one-dimensional diffusion of a gas through the polymer binder. The relevant parameters controlling the response time $\tau_{\text{resp}}$ are given by

$$\tau_{\text{resp}} \propto \frac{h^2}{D},$$

(7)

where $h$ is the paint thickness and $D$ is the gas diffusion constant for the binder. According to Eq. (7), the time response of pressure-sensitive paints may be improved by reducing the paint thickness or by increasing the diffusivity of the binder matrix. As the paint thickness is decreased, the amount of light emitted by the paint also decreases with a concomitant decrease in signal-to-noise ratio. Also, the gas diffusion constant of many polymers is so low that even very thin paint films will still exhibit unacceptably slow response times. Thus, a decrease in paint thickness is not an ideal solution for optimizing the paint response. A better solution is to significantly increase the gas diffusion constant of the binder matrix. This concept has led to a new class of pressure-sensitive paints based on porous binders.

Porous pressure-sensitive paints are based upon a matrix structure that is porous and relatively open to the test gas. The open structure allows for oxygen molecules to freely move in and out of the binder by gas diffusion processes. This is accomplished by drastically increasing the surface area of the binder, which enlarges the air-binder interface. This surface area enhancement modifies the diffusion coefficient shown in Eq. (7), creating an effective diffusion coefficient ($D_{\text{eff}}$) that is related to the fractal dimension of the porous structure. Thus, the response time decreases as the value of the effective diffusion coefficient increases.

Three types of porous binders have recently been developed for aerodynamic testing: thin-layer chromatography plate, anodized aluminum, and polymer/ceramic. Thin-layer chromatography plate is commonly used in chemistry laboratories and is composed of a thin layer (~250 μm) of silica gel. The disadvantages of the thin-layer chromatography plate are that it is fragile and limited to simple shapes. Anodized aluminum is created through an electrochemical process by etching small pores (~10-nm diameter) on an aluminum surface. The luminophore is deposited directly on the porous surface by chemical and physical adsorption. Anodized aluminum provides the fastest paint response times, but is limited by the choice of material and cannot be sprayed onto a model. Polymer/ceramic PSP is a hybrid that uses a small amount of polymer with a large amount of ceramic particles, as shown in Fig. 1. The resulting aggregate is a highly porous surface that allows for rapid
diffusion of the test gas. The primary advantage of polymer/ceramic paint is that it may be sprayed on a model, and offers reasonable response times.

Polymer/ceramic was selected for the current investigation because of its robust mechanical properties. The particular formulation created for acoustic testing is a water-based paint that was sprayed on one wall of the cavity. A slurry mixture was prepared by mixing 1.8 g of 0.4 μm rutile titanium dioxide (DuPont R-900) for every gram of distilled water. In order to separate any TiO₂ agglomerates, 12 mg of dispersant (Rohm & Haas D-3021) was added for every gram of water. The resulting slurry mixture was ball-milled for 1 h to mechanically break up TiO₂ agglomerates. The polymer (Rohm & Haas B-1035) was then stirred into the slurry mixture at a 3.5% weight ratio. The resulting polymer/ceramic formulation was then sprayed directly onto the test article. The chemical sensor, known as the luminophore, is the active ingredient of the paint formulation that is sensitive to local oxygen concentration. The luminophore selected for these tests was Tris(Bathophenanthroline) Ruthenium Dichloride (GFS Chemicals, CAS # 36309-88-3). This luminescent molecule was chosen because of its characteristically fast lifetime—approximately 5 μs at atmospheric conditions. The luminophore was dissolved in methanol, sprayed over the binder, and allowed to leach into the polymer/ceramic structure.

C. Dynamic response characteristics

The polymer/ceramic paint morphology has been tailored to optimize the frequency response characteristics of the paint. Before being applied to acoustic testing, however, the response characteristics must be evaluated in some manner. The fluid-dynamic flow field of a fluidic oscillator was used to demonstrate the fast response characteristics of these paints. A fluidic oscillator produces an oscillating jet when supplied with pressurized air, where the oscillation frequency varies with the supply pressure. The wave form of the oscillating jet approximates a square wave. As such, the flow field is rich in high-frequency content, and is ideal for calibrating the frequency response of the paint sensor. The pressure field of the impinging fluidic jet is a hydrodynamic pressure fluctuation \( (P/P_{\text{atm}} \approx 1.6) \), rather than an acoustic pressure fluctuation. The pressure levels induced by the fluidic jet are much greater than typical sound pressures. There is no expected difference in the frequency response characteristics of the paint due to the excitation mechanism (i.e., hydrodynamic versus acoustic) because the quenching mechanism remains the same. Gregory and Sullivan have shown that large-amplitude pressure fluctuations near the frequency response limit of the paint may induce a nonlinear response. Low-level pressure fluctuations such as acoustic pressures typically are not affected by the nonlinear response characteristics. Thus, it is presumed that the response for acoustic pressures will be at least as fast as the hydrodynamic response.

In the dynamic calibration experiments, the paint was excited with a 404-nm diode laser and the intensity response was recorded with a PMT. The paint response was compared with measurements from a collocated Kulite pressure transducer. Power spectra of the two signals are shown in Fig. 2. The 5.3-kHz fundamental frequency from the fluidic oscillator is clearly shown as the dominant peak in both the Kulite and pressure-sensitive paint power spectra. Higher-order harmonics are visible up through the fourth harmonic for the Kulite and the third harmonic for the PSP. Spurious harmonics at 2.7 and 8.0 kHz are also present in the Kulite data, but not in the pressure-sensitive paint data. This is an artifact of the large scale of the Kulite (∼2.5 mm) relative to the hydrodynamic jet diameter (∼1.5 mm), while the diameter of the laser spot for PSP is much smaller (∼0.5 mm). Thus, the absence of these spurious harmonics in the paint signal’s power spectrum is not due to a deficiency in the paint response. The peak magnitudes in the paint spectrum correlate well to the Kulite peak magnitudes, with the largest difference occurring at 10.5 kHz where the paint signal is only 2 dB down from the Kulite response. The signal-to-noise ratio of the instrumentation employed in these experiments was low, rendering the higher-frequency content of the flow field undetectable. The noise floor at −15 dB was higher than any frequency component above 20 kHz. Thus, the paint’s frequency response is flat to at least 15 kHz, and beyond this point the data are inconclusive because of the high noise level in the paint measurements. These response characteristics are sufficient for the current study, where the frequency of interest is on the order of 1.3 kHz.

D. Sensitivity

The luminophore molecules employed in porous paint formulations exhibit a nonlinear intensity response when subjected to a wide range of pressures, as shown in Fig. 3. The sensitivity is relatively high at very low ambient pressures, but the response is less sensitive near atmospheric conditions. When the paint is subjected to small pressure changes at atmospheric conditions, however, the response may be considered linear and Eq. (6) serves as a good description of the intensity response. The linear calibration co-
the mean pressure before the signals are recorded. For ex-

no way to offset the signals to remove the paint response to

pressure fluctuations from the mean pressure. Thus, there is

chemistry and optics of the system are unable to separate the

ments are inherently absolute, rather than ac-coupled. The

used for the measurements. Pressure-sensitive paint measure-

spheric conditions. Despite having a lower sensitivity, the

response of the polymer/ceramic paint formulation

is somewhat lower than the

is significantly greater than the response of

et al. Note that this dimin-

ished sensitivity is a consequence of the porous structure of

the paint formulation that enables fast response times, mak-

ing the luminophore molecules nearly quenched at atmo-

scopic pressure of 101.3 kPa produces a maximum pressure

ratio of ±0.28%. The intensity response of the polymer/

ceramic paint to this pressure fluctuation is ±0.058%. If a

14-bit photodetection system is used to record this signal, the

maximum bit change that will be recorded is ±10 counts (out

of a possible 16384).

Such a small change in measured signal is easily masked

by the noise in the measurement system. Thus, the signal-to-

noise ratio of the photodetector, along with the sensitivity of

the paint, are the limiting factors that establish the minimum
detectable level (Liu et al.). In the photon shot noise lim-

ited case, the signal-to-noise ratio is related to the photoelec-

tron capacity by

\[
\text{SNR} = \sqrt{\frac{V}{G \hbar v B_d}} = \sqrt{n_{pe}},
\]

where \(V\) is the photodetector output, \(G\) is the system gain, \(\hbar\) is Planck’s constant, \(v\) is the frequency, \(B_d\) is the electrical bandwidth of the detection electronics, and \(n_{pe}\) is the total number of photoelectrons collected over the integration time. An expression for the minimum detectable level is then given by

\[
\frac{(\Delta P)_{\text{min}}}{P} = \frac{1}{\sqrt{(n_{pe \text{ ref}})_{\text{max}}}} \left[ 1 + \frac{A P_{\text{ ref}}}{B P} \right] \times \left[ 1 + A + B \frac{P}{P_{\text{ ref}}} \right]^{1/2},
\]

where \(A\) and \(B\) are the linear calibration coefficients, \(P\) is approximately equal to \(P_{\text{ ref}}\) for acoustics measurements, and \((n_{pe \text{ ref}})_{\text{max}}\) is the full-well electron capacity of the CCD sensor. The 14-bit CCD sensor used in the current work has a full-well capacity of 255 000 electrons. When used with the polymer/ceramic paint formulation, this measurement system has a minimum detectable level of ±1.34% (±1.36 kPa at atmospheric conditions). Thus, the minimum resolvable pressure change is dependent upon the full-well capacity of the photodetector. This minimum level may be improved by averaging multiple images, because photon shot noise is a random noise source. If \(N\) images are averaged, then the minimum detectable level is reduced by a factor of \(N^{1/2}\). Yet another method for improving the minimum level is averaging pixels in a region, known as binning. This has the disadvantage of reduced

<table>
<thead>
<tr>
<th>Photodetector full-well electron capacity</th>
<th>Scroggin’s polymer/ceramic formulation(^a) (≥15 kHz response)</th>
<th>McGraw’s paint formulation(^b) (3.55 kHz response)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 000</td>
<td>383.3</td>
<td>121.4</td>
</tr>
<tr>
<td>150 000</td>
<td>177.0</td>
<td>56.0</td>
</tr>
<tr>
<td>255 000</td>
<td>135.8</td>
<td>43.0</td>
</tr>
<tr>
<td>500 000</td>
<td>97.0</td>
<td>30.7</td>
</tr>
</tbody>
</table>

\(^a\)References 28 and 29.

\(^b\)Reference 5.


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spatial resolution, however. A summary of these effects is presented in Table I, with a comparison of Scroggin’s polymer/ceramic paint formulation$^{28,29}$ with McGraw’s paint formulation$^2$ when 100 images are averaged. The sensitivity of McGraw’s paint is about three times that of the polymer/ceramic paint, yielding a 10-dB improvement in minimum detectable level, but at the expense of frequency response. Also evident in Table I is how the quality of the photodetector, expressed as full-well electron capacity, improves the minimum detectable level. The lower full-well electron capacities correspond to earlier camera designs,$^3$ while the higher values correspond to higher performance devices.

The main challenge in using pressure-sensitive paint for acoustic measurements is thus to resolve small intensity changes. Conversely, one advantage is that the paints do not have a rated maximum pressure that can be resolved. Microphones and piezoresistive pressure transducers have an upper pressure limit based on the mechanical properties of the diaphragm. The burst pressure can limit the usefulness of these conventional transducers for some nonlinear measurements, but pressure-sensitive paint is not limited in this regard.

III. EXPERIMENTAL SETUP

The experimental setup for the cavity pressure measurements is shown in Fig. 4. The cavity is made of 12.7-mm-thick acrylic, with overall dimensions of 216 mm length ($L_x$), 169 mm height ($L_y$), and 102 mm depth ($L_z$). The sound source used to drive the oscillations was a 100-W compression driver typically used on emergency vehicles (Southern Vehicle Products, D-60). The driver was mounted in the upper right-hand corner of the cavity ($x/L_x=0.9$, $y/L_y=1$, $z/L_z=0.5$), flush with the inner cavity wall and facing downwards. The corner is the most efficient location for exciting a rectangular cavity because it is always a pressure anti-node for any mode. A Kulite pressure transducer (XCQ-062-15D) was mounted in the forward upper-left corner, as shown in Fig. 4. The transducer signal was high-pass filtered at 500 Hz and low-pass filtered at 50 kHz. The Kulite measured the pressure fluctuations at the antinode, and provided a reference signal for phase-locking the pressure-sensitive paint data to the resonant oscillations.

The cavity was mounted with the $x$ dimension horizontal and the $y$ dimension vertical, with the speaker on the upper surface as shown in Fig. 4. The back surface of the cavity was a removable lid painted with polymer/ceramic PSP and bathophen ruthenium luminophore. Pressure-sensitive paint measurements were made with a Photometrics 14-bit CCD camera and an ISSI LM2 pulsed LED array ($\lambda \approx 470$ nm) for illumination. A 590-nm long-pass colored-glass filter was mounted on the camera to separate the excitation light from the paint luminescence. A camera shutter speed of 185 ms was selected in order to acquire sufficient luminescence from the paint. Since the acoustic pressure field is unsteady, phase-locking techniques were required to record time-resolved pressure-sensitive paint data. The pulsing of the LED array was synchronized with the pressure fluctuations measured by the Kulite pressure transducer through the gating function on a triggered oscilloscope. A variable delay was added to the oscilloscope’s TTL pulse with a Berkeley Nucleonics BNC-555 pulse/delay generator. Phase-locked time histories were recorded by varying the delay throughout the oscillation cycle. Thus, this system makes phase-averaged measurements of the unsteady pressure field. The excitation pulse width was typically 1.0% of the oscillation period, and each delay step was 8.3% of the period. Thus, there were 12 time steps evenly spaced throughout the complete oscillation cycle.

IV. DATA REDUCTION

Data reduction techniques were developed in order to successfully resolve acoustic-level pressures. The fidelity of pressure-sensitive paint measurements is primarily limited by shot noise in the CCD camera. Furthermore, the temperature sensitivity of PSP is a source of significant bias errors in most paint measurements. These two factors combined account for most of the errors in paint measurements.$^{32}$ Another potential source of error in pressure-sensitive paint measurements is any misalignment of the test object between the reference and test condition images. Particularly when low-level pressures are being measured, image misalignment errors can be substantial. These sources of error were reduced through use of the data acquisition and reduction techniques discussed as follows.

A. Shot noise

Random errors in the paint’s intensity signal are primarily attributable to shot noise in the CCD sensor. Shot noise is related to the electrical noise generated when the sensor converts the photons to an electrical signal, and in the digitization of that signal. Since shot noise is a random error, it may be reduced through averaging.$^{34}$ The error decreases with the square root of the number of samples acquired. Image averaging is a straightforward technique for reducing shot noise, but offers diminishing returns as the number of samples increases. In the current tests, 100 images were averaged to compile a single speaker-on image for each phase delay and test condition. The reference image was also an

![FIG. 4. Experimental setup of the cavity with pressure-sensitive paint.](image-url)
average of 100 images. Thus, the random shot noise for both
the speaker-on and reference images was reduced by an or-
der of magnitude by averaging. This in turn improves the
minimum detectable level by 20 dB.

B. Temperature effects

In aerodynamic testing in wind tunnels, temperature
variations can be a significant source of error for pressure-
sensitive paint measurements. If there is an unknown tem-
perature change between the reference and test condition
images, the temperature effect will produce a bias of unknown
magnitude in the pressure data. Researchers have compen-
sated for the temperature effect by using a temperature-
sensitive paint to correct the luminescent data.35 An alterna-
tive technique is to use a bi-luminophore paint, which allows
acquisition of the pressure and temperature data simulta-
tively.

The maximum temperature fluctuation induced by sound
pressure fluctuation is given by14

\[
T' = T_0 \frac{\gamma - 1}{\gamma} \frac{P'}{P_0}. \tag{10}
\]

Thus, for a ±500-Pa pressure fluctuation at atmospheric
pressure (101.3 kPa) and temperature (298 K), the maximum
temperature fluctuation will be ±0.42 K. The tem-
perature sensitivity of polymer/ceramic pressure-sensitive
paint is given as 1.24% change in intensity per degree
Kelvin.38 Despite these factors, temperature-induced er-
rors are negligible in the current set of experiments. The
painted acrylic surface has a fairly large heat capacity,
making the temperature oscillations in the paint layer sev-
eral orders of magnitude less than the maximum fluctua-
tion in the test gas. McGraw et al.5 made a similar argu-
ment for their paint tests, and showed experimentally that
temperature gradients induced by high-amplitude acoustic
fields could be safely neglected. Furthermore, Sakaue5
showed a temperature gradient of less than 0.01 K across
the entire painted surface of the cavity, even when driving
at high sound pressure levels (172 dB). This represents an
error in sound pressure of about 7 Pa. Thus, temperature
gradients and fluctuations are considered negligible, and
explicit temperature-correction schemes are unnecessary
for the subject work.

C. Image misalignment

Any slight displacement of the cavity between the speaker-on and reference images can cause substantial errors,
particularly if there are significant spatial inhomogeneities
in the paint layer. Image registration techniques are one attempt
at mitigating this issue.36 A more effective and straightfor-
ward correction, however, is to limit or eliminate the model
motion. In these tests, the cavity was securely fixed to the
table with rubber mounts and clamps. The rubber provided a
certain amount of damping and traction to prevent motion of
the box induced by speaker vibrations. Furthermore, it was
important to minimize the vibrations in the lab. Data quality
was significantly enhanced when images were acquired in a
quiet, vibration-free environment.

D. Data reduction procedure

A total of 200 images were acquired for each phase-
locked position within the oscillation cycle. The images were
acquired in 20 sets of 10 images, each set consisting of 5
speaker-on and 5 speaker-off conditions. Each image was
normalized by the average intensity value of the painted
surface. The 100 speaker-on images were averaged together, as
were the 100 speaker-off images. An intensity ratio was cal-
culated by dividing the speaker-off averaged image by the
speaker-on averaged image. This scheme was repeated for all
12 phase delays to compile a time history throughout the
oscillation cycle. The intensity images were then converted
to pressure through an in situ calibration from the Kulite
pressure transducer. The pressure data were then spatially
filtered with a two-dimensional low-pass spatial filter with a
frequency cutoff of 3 wavelengths per dimension. This filter
is useful in this application because sinusoidal fluctuations
are anticipated in the resonance cavity, and any higher spatial
frequencies will be due only to nonlinear effects and should
not exceed the third harmonic. After spatial filtering, a tem-
poral low-pass filter was applied to the pressure time-history
at each pixel location. The filter was a third-order
Chebyshev-II filter with the stop-band 20-dB down and a
cutoff frequency of 5 kHz.

V. RESULTS

The (1,1,0) mode within the cavity was excited by a
corner-mounted loudspeaker and the paint response was re-
corded. The pressure-sensitive paint results are then com-
pared with linear acoustic theory as well as measured data
from a conventional piezoresistive pressure transducer.

A. Linear modal theory

Despite the fact that the acoustic pressures in the cavity
are so high that nonlinear effects are anticipated, linear
modal theory provides a good first approximation of the
sound field. Pierce has derived modal theory for a rigid-
walled enclosure, based on a solution of the Helmholtz
equation.14 The resulting expression is the following spa-
tiotemporal response for the sound pressure:

\[
p(x,y,z,t) = \cos \left( \frac{n_x \pi x}{L_x} \right) \cos \left( \frac{n_y \pi y}{L_y} \right) \cos \left( \frac{n_z \pi z}{L_z} \right) e^{j \omega t},
\tag{11}
\]

Here \(n_x, n_y,\) and \(n_z\) are the mode numbers; \(L_x, L_y,\) and \(L_z\)
are the cavity dimensions; and the resonance frequency for a
particular mode is given by

\[
\omega(n) = c \pi \sqrt{\left( \frac{n_x}{L_x} \right)^2 + \left( \frac{n_y}{L_y} \right)^2 + \left( \frac{n_z}{L_z} \right)^2},
\tag{12}
\]

where \(c\) is the speed of sound. The dimensions of the subject
cavity were \(L_x=0.216 \text{ m}, L_y=0.169 \text{ m},\) and \(L_z=0.102 \text{ m}\) and
the experiments were performed at room temperature
(24.1 °C). With these parameters, Eq. (12) indicates that
the resonant frequency should be 1298 Hz for the (1,1,0)
mode. Equation (11) yields the pressure distribution inside
the cavity volume. The calculated surface-pressure field
on the cavity wall is shown in Fig. 5, with the amplitude scaled to match the experimental data. The nodal lines in the pressure field are along the central axes of the \(x\) and \(y\) coordinates (\(x\) is horizontal and \(y\) is vertical in the figure).

**B. Pressure-sensitive paint results**

The frequency of the driving signal was adjusted such that a maximum pressure amplitude was obtained near the resonant frequency for the \((1,1,0)\) mode. The tuned driving frequency was 1286 Hz, which is within 1% of the predicted resonance frequency. Figure 6 shows pressure-sensitive paint data for the \((1,1,0)\) mode shape at an SPL of 145.4 dB. This pressure map represents one phase-averaged point within the oscillation period, at the condition when the anti-node pressure is nearly maximum. The pressure distribution compares favorably with the general distribution from linear theory shown in Fig. 5. There are some minor differences between the paint data and the theoretical solution: the nodal lines are slightly curved, and the pressure in the center of the resonance cavity is slightly lower than ambient pressure. Furthermore, the maximum amplitudes in the left corners are slightly greater than the pressure amplitudes in the right corners. These differences may be attributed to nonlinear effects at the high sound pressure levels of these tests (145.4 dB).

Figure 7 shows the spatial pressure distribution at three phase-averaged time steps, separated by 90° phase within the oscillation cycle. Figures 7(a) and 7(c) show the antinode pressures at...
their maxima and minima. Figure 7, however, shows a nearly uniform pressure across the cavity, as expected. The uniform pressure distribution at this time step confirms the isothermal assumption.

One sample time-history from the paint data at a single point is shown in Fig. 8. The signal from the Kulite pressure transducer is compared with the analytical solution and the pressure-sensitive paint data points. The paint data results from averaging the signal in a 10-pixel square window in the bottom, left corner of the cavity $(x/L_x=0, y/L_y=0)$. The error bars on the PSP data indicate an average uncertainty of ±12.5 Pa.

The difference between the Kulite transducer data and the linear theory, indicating the level of nonlinearity. The data points are the difference between the PSP data and the linear theory. The paint data have a bias error between 50 and 100 Pa, when compared to the Kulite data. This bias error may be due to uncertainty in the magnitude and time scale of the in situ calibration process, and ultimately is about one order of magnitude larger than the 115.8 Pa minimum detectable level predicted by Eq. (9).

A cross section of the paint data along the left vertical edge $(x/L_x=0)$ of the cavity is shown in Fig. 10. Each curve represents a separate time step, spaced equally throughout the period of 777 $\mu$s. The node is clearly visible at the midpoint of the wall $(y/L_y=0.5)$, where the pressure fluctuations are nearly zero. There is some distortion visible in the spatial wave form, but the data largely resemble the linear numerical results of Vanhille and Campos-Pozuelo.17 A pressure plot of the phase-averaged rms pressure fluctuations is shown in Fig. 11. This plot also indicates the node locations across the end wall of the resonance cavity, taking into account the entire cycle of the pressure fluctuation. This plot is a concise representation of the large volume of data generated by the pressure-sensitive paint measurements.

C. Discussion

The level of the pressure amplitudes measured in these experiments is on the order of 500 Pa. It is estimated that this pressure-sensitive paint system and data reduction methodology are capable of reliably resolving pressure amplitudes as low as 50 Pa (125 dB). Since a 10-pixel square region was averaged from the 100-image average at each data point, the theoretical SNR was improved by a factor of 100. Thus, the minimum detectable level for this test was 115.8 dB, which is 9 dB lower than the experimentally estimated minimum of 125 dB.

A unique characteristic of porous paint formulations can be employed to improve the pressure sensitivity. Figure 3...
shows that the slope of the calibration curve near vacuum conditions is approximately 3.7 times higher than the slope at atmospheric conditions. If the mean pressure can be reduced, then the higher sensitivity of the paint formulation at these pressures can be advantageously exploited. A second alternative is to alter the test gas within the resonance cavity. If an inert gas such as nitrogen or argon at atmospheric pressure is injected with trace amounts of oxygen, then the resulting gas mixture approximates air at low mean pressures as sensed by the paint.

One significant advantage of the current test is that the pressure field is repeatable, which allows for phase-averaging techniques to be employed. If a transient pressure field must be measured, then other techniques and instrumentation can be utilized. A high-speed CCD camera may be used, although the lower signal-to-noise ratio of these cameras will establish a higher minimum-detectable-level. Alternatively, a point measurement could be acquired with a laser-scanning system for illumination and a photomultiplier tube for detection. This type of system offers much higher light intensity, which improves the signal-to-noise ratio for real-time measurements.

A hallmark of the polymer/ceramic paint utilized in these tests is that it is a very bright paint formulation. The titanium dioxide particles present in the paint not only enhance the response time, but also serve as reflective particles that make the paint much brighter than most other formulations. This allows for a very short shutter exposure time (185 ms), which decreases thermal noise in the image. The total amount of light integrated by the camera was 185 ms: 100 images were acquired at 185-ms each, but the excitation light was pulsed such that the paint was illuminated for 1% of the exposure time. This contrasts with the 4-s of light required for Brown’s tests of a NACA 0012 airfoil in a low-speed wind tunnel.14 He found that rms error was adequately reduced by averaging 8 wind-on images, with a 500 ms exposure for each image. The total pressure gradient over the airfoil surface was about 4 kPa. The significant limiting error source in his tests was a temperature change as the wind tunnel cooled down after the run. In the current acoustic PSP tests, which are not hindered by temperature problems, the resolved pressure gradient is on the order of 1 kPa and the total integrated light is 185 ms.

VI. CONCLUSIONS

Pressure-sensitive paint was used to measure sound pressure fluctuations at a frequency of about 1.3 kHz. The (1,1,0) mode shape within a rigid, rectangular cavity was effectively resolved with the PSP system. This work overcomes two significant challenges that have limited pressure-sensitive paint measurements of acoustic pressures in the past. First, the excellent frequency response characteristics (≥15 kHz) of the porous paint formulations have allowed time-resolved measurements of the unsteady fluctuations. The second challenge addressed was the sensitivity limitation of pressure-sensitive paints. Data acquisition and reduction techniques were developed to extend the resolvable pressure limitation of most paints. Pressure amplitudes on the order of 500 Pa (145 dB) were measured, and it is estimated that this system is capable of measuring pressure amplitudes as low as 50 Pa (125 dB). Furthermore, the paint system has no theoretical limit on the maximum pressure levels that can be measured, making the system ideal for nonlinear acoustics measurements. The paint measurements in the current tests compared exceptionally well with both linear modal theory and experimental measurements with a Kulite pressure transducer. These tests demonstrate the utility of pressure-sensitive paint for making acoustics measurements. The pressure-sensitive paint data provide a complete time-history of the pressure at over 137 000 pixel locations across the 365-cm² area of the cavity. As such, the paint system is a distributed array of nano-scale optical microphones. The pressure-sensitive paint system described in this work may be applied to tests where high spatial resolution is required, such as nonlinear acoustics, ultrasonic measurements, and acoustics in MEMS devices.

ACKNOWLEDGMENTS

Funding for this work was provided by the NASA Graduate Student Researchers Program through NASA Glenn Research Center and NASA Langley Research Center. The Boeing Company has loaned the CCD camera that was used in these tests. The authors also wish to thank Luc Mongeau for his comments and suggestions. Funding for this work was provided by the NASA Graduate student Researchers Program Center. The Boeing Company has loaned the CCD camera that was used in these tests. The authors would like to thank Tim Bencic of the Optical Instrumentation Technology Branch at NASA Glenn, who provided lab space for the dynamic calibration experiments, as well as discussions that were the progenitor for this work. The authors also wish to thank Luc Mongeau for his comments and suggestions.

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