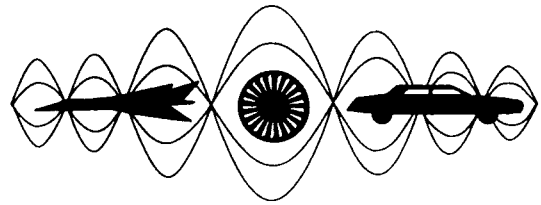

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REAL-TIME VIBRATION MODE IMAGING USING PHOTOREFRACTIVE HOLOGRAPHY

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ABSTRACT

Advances in optics over the last two decades have led to the development of optical processing mechanisms in photorefractive materials that provide unique capabilities for intelligent sensing applications. These capabilities include adaptability to environmental effects, image correlation, and optical computing. This paper describes the utilization of photorefractivity for performing noncontacting optical vibration detection that is most useful for small peak amplitudes less than $\lambda/4\pi$. Multi-wave mixing with synchronous detection allows measurement of both the vibration amplitude and phase of a vibrating surface directly as a function of the excitation frequency. Narrow bandwidth detection with flat frequency response can be achieved at frequencies above the photorefractive response (~100 Hz). A minimum detectable displacement amplitude of a few picometers has been demonstrated for a point measurement, with the possibility of further improvement. Full-field imaging of vibrating surfaces is performed in a manner that employs the adaptive properties of the photorefractive effect for real-time processing. The result is an output image intensity directly proportional to the vibration amplitude for small amplitudes, making this approach complementary to other electronic speckle interferometry methods. An all optical vibration measurement technique is demonstrated by employing laser thermoelastic heating for excitation. Measurements of a vibrating stainless steel plate are presented showing the capabilities of the photorefractive approach for vibrational spectral analysis.

INTRODUCTION

Vibrational motion is often used to measure or characterize material properties. Many optical techniques have been developed for noncontacting measurements; most of these methods have similar sensitivities and are based on coherent optical interferometry[1,2].

Adaptive interferometry, which uses the photorefractive effect in optically nonlinear materials, offers a potentially powerful method for real-time optical imaging processing and automatic correction for environmental effects.[3,4] Photorefractivity employs optical excitation and transport of charge carriers to produce a hologram of an interference pattern inside the nonlinear optical material. The spatially- and temporally-modulated charge carrier distribution is a direct measure of the phase information impressed onto the optical object beam by the vibrating surface. This hologram stores phase information from all the surface points on the vibrating specimen simultaneously. The hologram can be detected via diffraction of a readout beam off the photoinduced-volume grating. A method has been developed for vibration detection[5,6] that employs the photorefractive effect in a synchronous detection manner.[7] This method phase modulates the object and reference beams such that an alternating photorefractive grating at a fixed beat frequency is established within the material regardless of the specimen vibration frequency. The intensity of a readout beam scattered off the photoinduced grating directly measures the vibrational amplitude and phase. It can be used for spectral analysis with a response proportional to the Bessel function of order one, providing a linear output for small amplitudes. The method accommodates rough surfaces and exhibits a flat frequency response above the photorefractive cutoff frequency. A minimum detectable displacement of 2 picometers has been recorded, and further improvement is possible. This paper further describes the ability of this photorefractive method, when coupled with laser thermoelastic heating, to provide an all-optical vibration detection approach that is intrinsically calibrated and capable of real-time full-field imaging.

Typically, nonphotorefractive interferometric methods do not image more than one surface point at a time. However, since the photorefractive process records a volume hologram of all vibrating surface points simultaneously, imaging can be readily performed. Both four-wave and two-wave mixing configurations have been employed for reading out the vibration-induced phase grating image. Results are presented for vibration modes of a free, square stainless steel plate with diffusely reflecting surfaces that is driven piezoelectrically at one corner or by laser thermoelastic heating at points on its surface.

PHOTOREFRACTIVE OPTICAL VIBRATION DETECTION

Figure 1 shows the experimental setup for optical detection of a vibrating plate. A diode-pumped Nd:YAG laser source (532 nm, 200 mW) is split into object and reference beams. The excited vibrational modes of the plate phase modulate the object beam. The reference beam is phase modulated by an electro-optic modulator (EOM) at a fixed specified modulation depth.

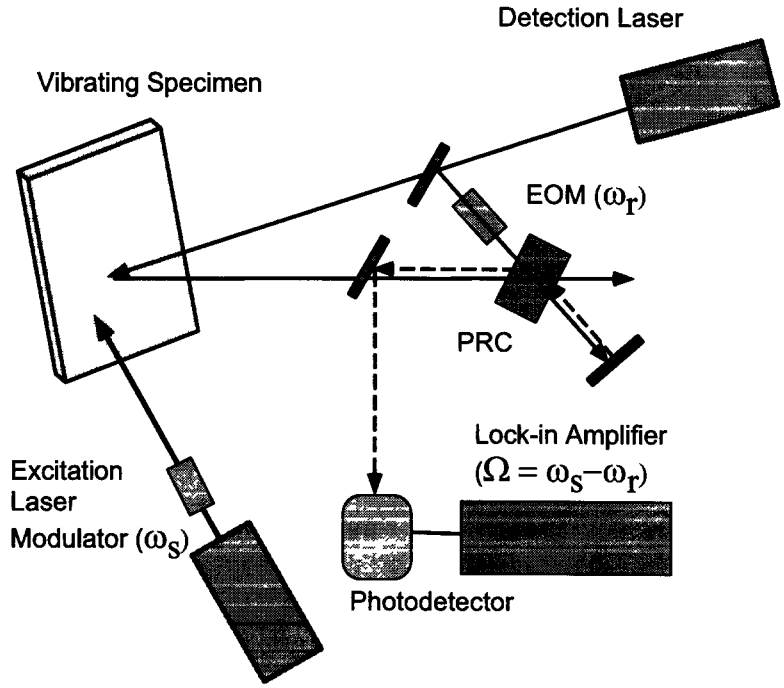


Figure 1. Photorefractive detection of vibration. EOM is "electro-optic modulator", PRC is bismuth silicon oxide "photorefractive crystal".

The object and reference beams are then combined inside a bismuth silicon oxide (BSO) photorefractive crystal. A four-wave mixing configuration is used for readout of the photorefractive index grating for the single-point measurements. The reference beam is reflected back into the crystal along a counter-propagating path that matches the Bragg angle of the photorefractive grating in the medium. The resulting scattered wave is then sampled at the plate beamsplitter and deflected toward the photodetector. Subsequently, the photodetector signal is processed with conventional electrical lock-in methods to provide a measurement bandwidth of 1 Hz. A diagram of the 1.5 inch square, 0.015 inch thick, Type 304 stainless steel plate specimen is shown in Figure 2; the plate can be driven piezoelectrically at one corner or by laser thermoelastic heating at any position (points referred to later are designated as A, B, C in the figure).

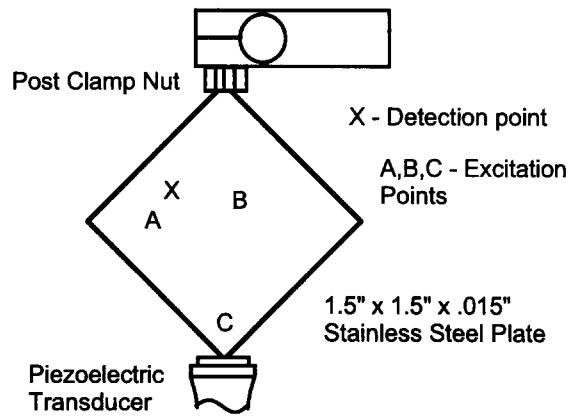


Figure 2. Stainless steel plate geometry.

DETECTION PROCESS MODEL

The photorefractive detection process can be modeled using one-dimensional electromagnetic plane wave analysis. Both optical beams reaching the photorefractive crystal are phase modulated by their respective path lengths. In addition, the signal beam is modulated by the surface vibration $\xi(t) = \xi_0 \sin(\omega_s t + \varphi_s)$ as $\Phi_s = \Phi_{s0} \sin(\omega_s t + \varphi_s)$, $\Phi_{s0} = \frac{4\pi\xi_0}{\lambda}$ and the reference beam is phase modulated by the EOM according to $\Phi_r = \Phi_{r0} \sin(\omega_r t + \varphi_r)$. The interference distribution and subsequent charge migration within the crystal generate a corresponding space charge electric field distribution, E_{sc}. The dynamic behavior of this field is controlled by the charge carrier mobility and trapping that produces, in the diffusive operation regime, a single relaxation time response given by $\frac{\partial E_{sc}}{\partial t} + \frac{E_{sc}}{\tau} = \frac{iE_q}{\tau} \frac{\Delta I(\vec{r},t)}{I_0}$, where τ is the material response time, $\frac{\Delta I(\vec{r},t)}{I_0}$ is the interference fringe contrast, and E_q is the maximum achievable space-charge field, controlled by the concentration of available charge trapping sites and the fringe spacing. In this configuration, the photorefractive crystal acts as a mixing and low-pass filtering element, providing the benefits of lock-in detection. Therefore, the space charge field responds to slowly varying phase modulations occurring within the material response time, allowing only the terms around the difference frequency, $\Omega = \omega_s - \omega_r$, $\Omega\tau \le 1$, to be important. The space-charge field modulates the local refractive index through the linear electro-optic effect. This effect creates, within the crystal, a diffraction grating that contains the low frequency phase information desired.

In the four-wave mixing arrangement, the reference beam that passes through the crystal is reflected back and diffracts into the signal beam, see Figure 1. The magnitude of the index of refraction is proportional to the space charge field and to the orientation-dependent electro-optic effect in BSO. The diffracted beam intensity is a direct measure of the grating established and produces DC and AC output photodetector voltages given by

$$\frac{V_{DC}(\Phi_{s0})}{V_{DC0}} = J_0^2(\Phi_{s0}), \qquad V_{DC0} = V_{DC}(\Phi_{s0}=0) = C J_0^2(\Phi_{r0}) \tag{1}$$

$$\frac{V_{AC}(\Phi_{s0})}{V_{DC0}} = J_0(\Phi_{s0}) J_1(\Phi_{s0}) \left[\frac{J_1(\Phi_{r0})}{J_0(\Phi_{r0})} \frac{4}{\sqrt{1+\Omega^2\tau^2}} \right] \cos\left(\Omega t + \psi + (\varphi_s - \varphi_r)\right) \tag{2}$$

where $\tan(\psi) = \Omega\tau$. Since the reference modulation and the photorefractive time constant are known, measurement of the DC and AC voltage magnitudes provides a direct calibration of the vibration amplitude in terms of the known optical wavelength through

$$\frac{2J_1(\Phi_{s0})}{J_0(\Phi_{s0})} = \left| \frac{V_{AC}}{V_{DC}} \right| B(\Phi_{r0}, \Omega\tau) \approx \Phi_{s0} = \frac{4\pi\xi_0(\omega)}{\lambda}, \quad \text{for} \quad \Phi_{s0} << 1 \tag{3}$$

where $B(\Phi_{r0}, \Omega\tau)$ is the instrumental parameter given by the bracketed term in Equation 2. The recorded spectrum showing the DC and AC response of two separate modes is shown in Figure 3. Measured vibration amplitude DC and AC signals supporting Equations 1, 2, and 3 are shown in Figure 4 for a single mode with $\Phi_{r0} \approx 1.1$ and $\Omega\tau \approx 1$. In this figure, the vibration amplitude was determined by the best fit of the data to Equation 3 at small drive amplitudes.

LASER EXCITATION

Vibration measurement can be totally optical if an optical excitation source is used with the optical detector. Laser light striking a solid heats it, producing a strain that is modulated in the same manner as the laser light is modulated, i.e. chopped. In addition to being noncontacting, such optical excitation offers significant potential for selectively exciting certain vibrational modes because the region of excitation can be controlled to enhance the response of one vibrational mode over another.

A continuous wave, 700 mW average power, diode laser was used as indicated in Figure 1. An acousto-optic modulator chopped the excitation source, producing a modulation component at the frequency of interest. The chopping was synchronized with the electro-optic modulator as the measurement frequency was swept through several vibrational modes. Figure 5 shows the effect of laser excitation at three points around

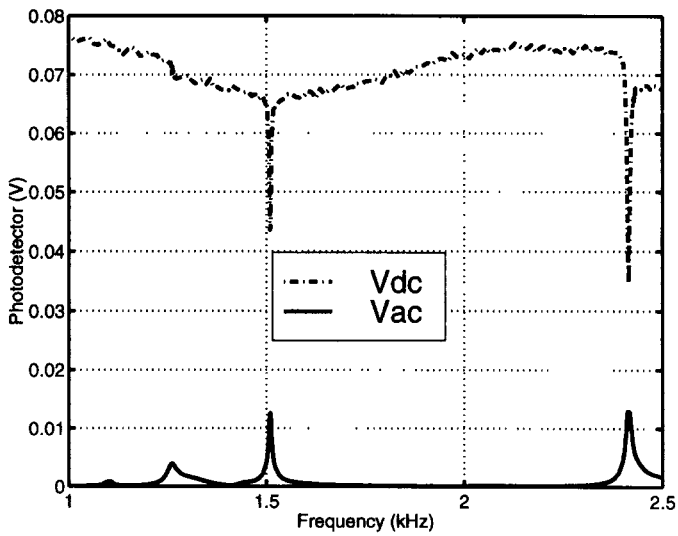


Figure 3. Photodetector DC and AC voltages showing two vibrational modes of the square stainless steel plate.

the plate (A, B, C illustrated in Figure 2). Several plate modes are identified in Figure 5, one with nodal lines traversing across the plate from corner to corner at 1.5 kHz, and one with a vertical nodal line from the top corner to the bottom and two parallel lines closer to the left and right corners at 2.4 kHz; these are better described in Figures 6 and 7. The optical source position selects between these two modes—excitation at Point A selected against the 1.5 kHz mode, B selected against the 2.4 kHz mode, and C selected against both modes. These results suggest that greater excitation occurs when the optical absorption spatial profile matches the vibrational mode spatial profile.

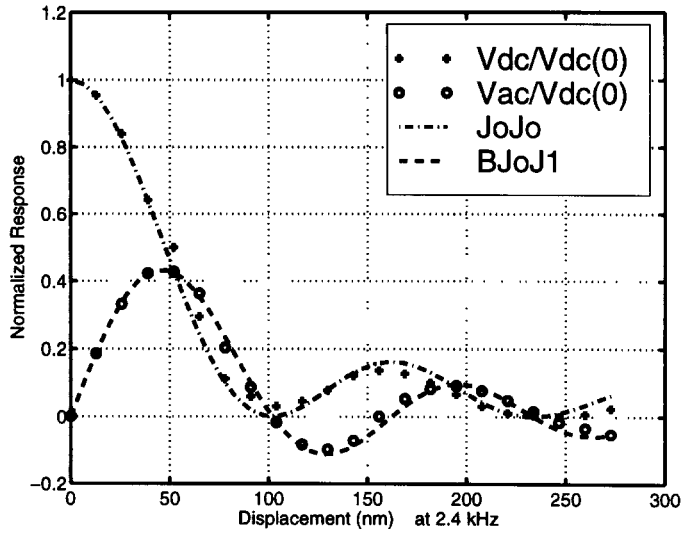


Figure 4. Measured DC and AC photodetector voltages for a single resonance as a function of the vibration amplitude.

VIBRATION IMAGING

Since the optical interference and the photorefractive effect occur throughout the photorefractive material, the single point detection method described above can be generalized to form an image of the vibration over the surface of the plate. The volume character of the photorefractive process creates a grating distribution that locally records the phase modulation measured from each point of the specimen surface as long as the surface is accurately represented within the interference volume. The output beam intensity from the detection process can be measured by an array of detectors, or even a highly pixelated device, such as a CCD camera. Each pixel records the local intensity at a point on the specimen and produces an output proportional to that point's displacement. The multiplexed scheme used to read out CCD arrays introduces some problems with the synchronous or lock-in approach described earlier for point detection. A similar lock-in enhancement technique could be developed for this purpose. This capability for imaging is a significant enhancement of the photorefractive measurement method, compared with other optical interferometric methods, as it provides real-time full-field measurement at virtually any vibration frequency.

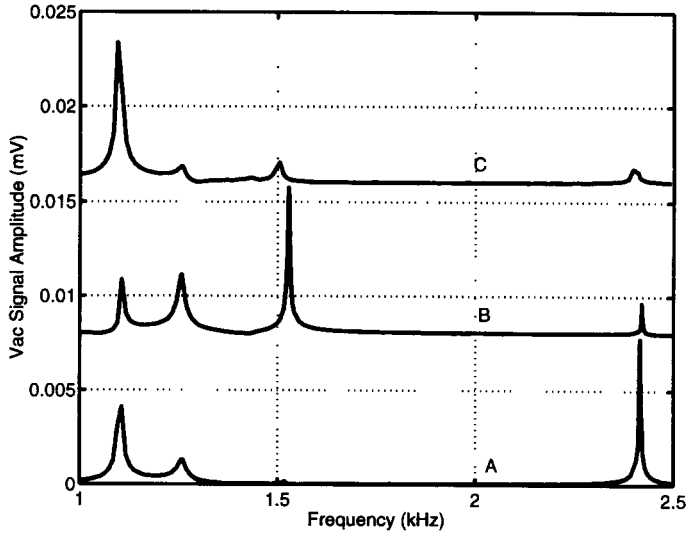
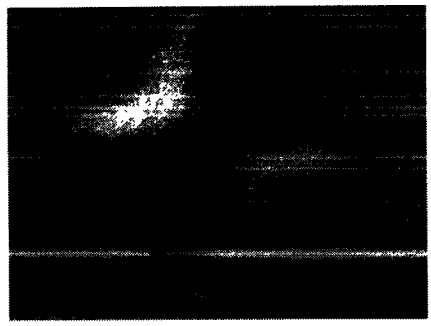


Figure 5. Vibrational response with the source laser excitation in positions A, B, C as identified in Figure 2.



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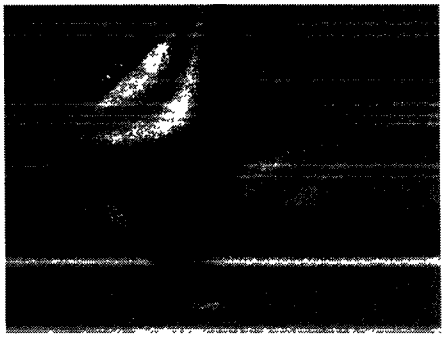

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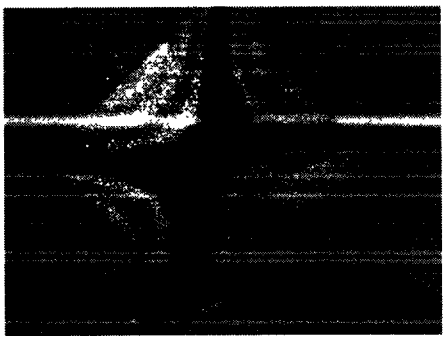

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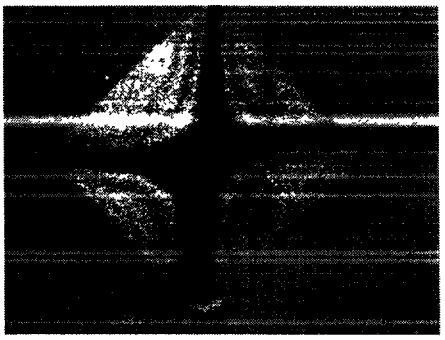

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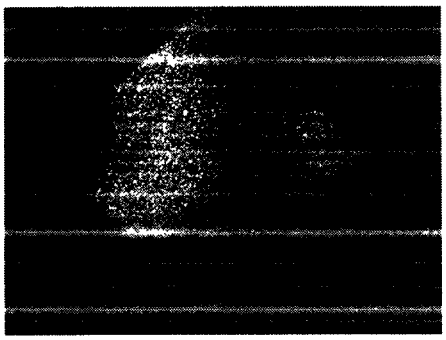
Figure 6. Vibrational images of a free square plate at 1.5 kHz. Maximum amplitude is approximately (a) 45 nm, (b) 90 nm, (c) 180 nm, (d) 270 nm.



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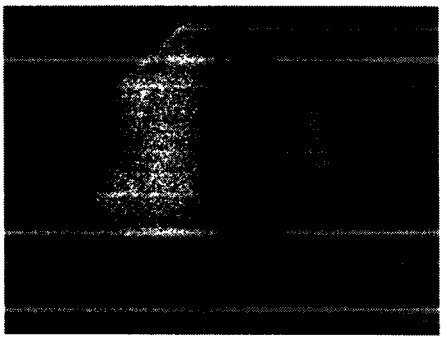

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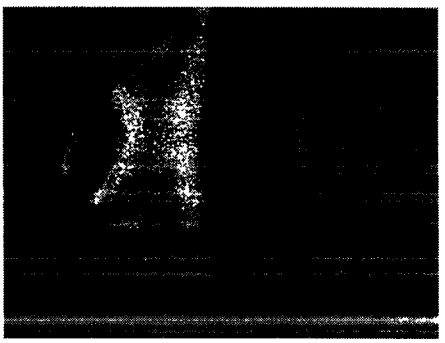

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Figure 7. Vibrational images of a free square plate driven at 2.4 kHz. Maximum amplitude is approximately (a) 45 nm, (b) 90 nm, (c) 180 nm, (d) 270 nm.

A two-wave approach, based on polarization rotation through anisotropic self-diffraction,[8,9] was used for imaging as it offers improved light throughput from diffusely reflecting surfaces compared to the four-wave method. Figures 6 and 7 show images of the modes at 1.5 and 2.4 kHz, respectively, excited by a contact piezoelectric transducer at one corner. A piezoelectric excitation source was used to generate displacements larger than the approximately 80 nm produced by the available optical source. The nodal lines are clearly defined, and the relative phases of the vibration displacements are indicated by the light and dark areas. The entire modal pattern can be made to switch from light to dark by varying the offset frequency, $\Omega/2\pi$, between the object and reference excitations. This provides a powerful tool for visual mode searching and suggests processing methods that can be employed to enhance the detectability of specific modes. The minimum detectable displacement in the imaging mode (~1 nm) is much larger than for the point detection method (~2 pm) as no post electronic lock-in processing was performed.

Figures 6 and 7 illustrate the character of the photorefractive measurement as the vibration amplitude is increased. Equation 2 and Figure 4 show that the vibration response signal becomes nonlinear for amplitudes greater than about 20 nm and peaks at 45 nm, $\lambda/4\pi$ for a laser wavelength of 532 nm. This makes the photorefractive approach primarily useful for small vibration amplitudes where linear response is obtained. For vibrating surfaces with large overall vibration amplitudes, the position on the surface where the peak response (~45 nm) is observed moves closer to nodal positions. The image then resembles the shape of the nodal points within the vibrating surface; hence, the technique becomes a "nodal line" indicator for large vibration amplitudes.

CONCLUSIONS

A photorefractive, optical, lock-in, vibration spectral measurement method for quantitative determination of the vibration amplitude has been described. The method uses optical synchronous or lock-in detection, which can also include conventional electrical lock-in detection for narrow bandwidth, high sensitivity measurements. Readout methods employing four-wave or two-wave mixing produce an output intensity directly proportional to the amplitude of the vibration being measured, for small amplitudes relative to the optical wavelength, and provide the capability for mechanical phase measurement if synchronous excitation is used. Vibration imaging of a diffusely scattering surface showed minimum detectable displacements in the 1 to 5 nm range. The method is capable of flat frequency response over a wide range above the cutoff of the photorefractive effect and is applicable to rough surfaces. At large vibration amplitudes the technique becomes a "nodal line" indicator.

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