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Vibration modal analysis using all-optical photorefractive processing

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ABSTRACT

A new experimental method for vibration modal analysis based on all-optical photorefractive processing is presented. The method utilizes an optical lock-in approach to measure phase variations in light scattered from optically rough, continuously vibrating surfaces. In this four-wave mixing technique, all-optical processing refers to mixing the object beam containing the frequency modulation due to vibration with a single frequency modulated pump beam in the photorefractive medium that processes the modulated signals. This allows for simple detection of the conjugate wavefront image at a CCD. The conjugate intensity is shown to be a function of the first-order ordinary Bessel function and linearly dependent on the vibration displacement induced phase δ, for $\delta = 4\pi\xi/\lambda << 1$ where ξ is the vibration displacement and λ is the source wavelength. Furthermore, the results demonstrate the unique capabilities of the optical lock-in vibration detection technique to measure vibration signals with very narrow bandwidth (< 1 Hz) and high displacement sensitivity (sub-Angstrom). This narrow bandwidth detection can be achieved over a wide frequency range from the photorefractive response limit to the reciprocal of the photoinduced carrier recombination time. The technique is applied to determine the modal characteristics of a rigidly clamped circular disc from 10 kHz to 100 kHz.

2. INTRODUCTION

Many optical techniques for vibration detection used in applications such as laser ultrasonics are based on time domain processing using homodyne or heterodyne interferometry. [1] Vibration displacement amplitudes are recorded through interference at the photodetector and subsequent signal processing. [2] Wide bandwidth is typically employed to obtain real-time surface motion under transient conditions. Some applications, such as structural analysis, are better served by measurements in the frequency domain that record the randomly or continuously excited vibrational spectrum. A significant signal to noise ratio improvement is gained by the reduced bandwidth of the measurement compared to the time domain methods, but at the expense of additional processing and complexity. A shortcoming of optical approaches has been the sensitivity to speckle reflections from the specimen surface. This can be corrected by limiting detection to a single speckle or by use of self-beating interferometers, such as the Fabry-Perot. A potentially more powerful method is to utilize the photorefractive effect in optically nonlinear materials. This method provides an active mechanism for compensation using the spatial and temporal characteristics of photorefractivity.

Several all-optical photorefractive processing measurement methods of vibration in the frequency domain have been proposed using photorefractive two and four wave mixing in select materials.[3-5] Most provide a response that is a nonlinear function of the specimen vibration displacement amplitude and do not provide a measure of the vibration phase. We present an extension of those earlier methods that uses an optical lock-in approach for vibration detection and modal analysis that directly measures vibration amplitude and phase with a response proportional to the Bessel function of order one and is, therefore, linear for small amplitudes. The method accommodates rough surfaces and utilizes photorefractive processing in conjunction with a single, fixed frequency narrow bandwidth detection system.[6] The method is applied to accurately determine several resonant modes of a rigidly clamped circular disc.

3. EXPERIMENTAL SETUP

The four-wave mixing experimental setup is shown in figure 1. An argon laser source at 514 nm, 200 mW, is split into two legs, an object and reference. The object beam is reflected off a specimen undergoing continuous vibration. The excited vibrational modes of the specimen determine the frequency-dependent displacement amplitude of the sample surface, which is transferred into phase modulation of the object beam. The reference beam is frequency modulated by an electro-optic modulator (EOM) at a fixed modulation depth. The modulated beams are then combined and interfere inside a bismuth silicon oxide (BSO) photorefractive crystal (PRC) at an external angle between the beams of 55 degrees. A four-wave mixing configuration is used for demodulation of the photorefractive interference grating produced within the crystal. 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 or conjugate signal beam is then sampled at the plate beam splitter and deflected toward the photodetector.

4. FREQUENCY-BASED PROCESSING

In the above configuration, the PRC acts as a mixing and low pass filtering element providing the benefits of lock-in detection.[7] The measured signal intensity can be calculated from the time-dependent photorefractive 1st order response theory in the single grating approximation.[8] The result, retaining only the most dominant terms, is described by the following equation[9,10]

$$I(t) \sim J_0(\delta_1) J_1(\delta_1) J_0(\delta_2) J_1(\delta_2) \frac{\cos(\Omega t + \Psi - (\varphi_1 - \varphi_2))}{\sqrt{1+\Omega^2\tau^2}} \qquad (1)$$

where τ is the photorefractive time constant, $\Omega = \omega_2 - \omega_1$ and $\Psi = \tan(\Omega\tau)$. Here, the predicted intensity is proportional to the vibration displacement (ξ) for small amplitudes, $\delta = 4\pi\xi/\lambda << 1.1$. Also, the strong dependence of the output intensity on the path dependent phase shift ($\varphi_1 - \varphi_2$) described in equation (1) can be reduced by shifting the measurement to a fixed offset frequency (Ω). This method of operation is what we call the Swept Network Mode in analogy with common electrical frequency analysis measurements.

In this Swept Network Mode, the signal excitation and reference modulation are maintained coherent at a fixed frequency difference, $\Omega/2\pi = 25$ Hz. This operational mode insures that an AC or beat component of the conjugate signal intensity at 25 Hz is always present at the photodetector and its intensity is given by equation (1). The output is demodulated by a conventional lock-in amplifier yielding a measurement bandwidth that can be set less than the PRC bandwidth. In this manner, both the vibration amplitude and phase are directly measured. This method discriminates against static or time varying phase shifts outside the lock-in bandwidth and can be extended to vibration frequencies from the reciprocal of the

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photorefractive response time (67 Hz) to the reciprocal of the recombination time (estimated 10 MHz) of the PRC. However, two closely spaced vibrational modes cannot be resolved beyond the response time of the PRC, in this case approximately 67 Hz.

5. VIBRATION MODAL ANALYSIS

The swept spectrum (displacement amplitude versus frequency) of a vibrating mirror specimen (solid) and the noise level (dotted) are shown in figure 2, obtained with a net demodulated power on the detector of 5 μW and a bandwidth of 1 Hz. The pronounced fundamental mechanical resonance at 18.6 kHz is clearly shown, along with the noise level corresponding to a minimum displacement sensitivity of approximately 0.02 Angstroms. The configuration of figure 1 allowed quantitative determination of the displacement amplitude by comparison to the known response of the EOM calibrated with homodyne intereferometry. The corresponding phase for the mirror specimen spectrum is shown in figure 3. Figure 4 shows the measured linear response of the displacement amplitude at 15 kHz with respect to the mirror motion and figure 5 the EOM contribution in equation (1) in terms of the Bessel function product. These data support the phenomenological model predicting equation (1). With above characterization in place, the method was applied to determine the resonant vibrational modes of a simple structure.

In this case, the structure to be analyzed was a rigidly clamped circular disc (a simple flat-bottomed hole specimen). Six theoretical mode shapes of the specimen are shown in figure 6, regions of relative phase are shown along with nodal lines and circles. In addition, the corresponding eigenfrequencies for these shapes are given which have been calculated using an analytical plate wave model with the same thickness, diameter and elastic modulus parameters as the actual flat-bottomed hole specimen.

From observation of the theoretical mode shapes, the position of the probing beam on the surface of the specimen can be seen to have a significant effect on the measurement of the vibration spectrum as demonstrated in figure 7. The solid line is a frequency scan done with the probing beam positioned in the center of the disc. Only the presence of the first and fourth mode peaks are detected because there are no nodal lines (zero displacement) at this position. Meanwhile, the second, third, fifth and sixth mode peaks remain small or undetected. However, by positioning the probing beam just off-center during the scan (dashed line), peaks for these modes can be detected. Furthermore, the calculated eigenfrequencies (small circles) in in figure 6 are compared with these experimentally obtain resonant peaks. In all cases, good correlation between the theory and experiment was obtained (the sixth calculated mode peak is just beyond 100 kHz), demonstrating the usefulness of the technique to provide accurate vibration modal analysis results.

6. CONCLUSIONS

A new experimental technique for vibration modal analysis based on all-optical photorefractive processing has been presented. The method uses an optical synchronous or lock-in detection and also includes electrical lock-in detection. Sub-Angstrom level detectability has been demonstrated with fixed narrow bandwidth. The method is capable of flat frequency response over a large range, from the cutoff of the photorefractive effect to the high megahertz region and is applicable to rough surfaces. The capability of the method to make precise measurements has been demonstrated experimentally and, in particular, the mode shapes of a flat-bottomed hole specimen have been accurately identified from 10 kHz to 100 kHz. In addition, the photorefractive lock-in vibration detection method can be configured for high sensitivity, linear vibration imaging. Work on this full-field view approach is in progress.

7. ACKNOWLEDGEMENTS

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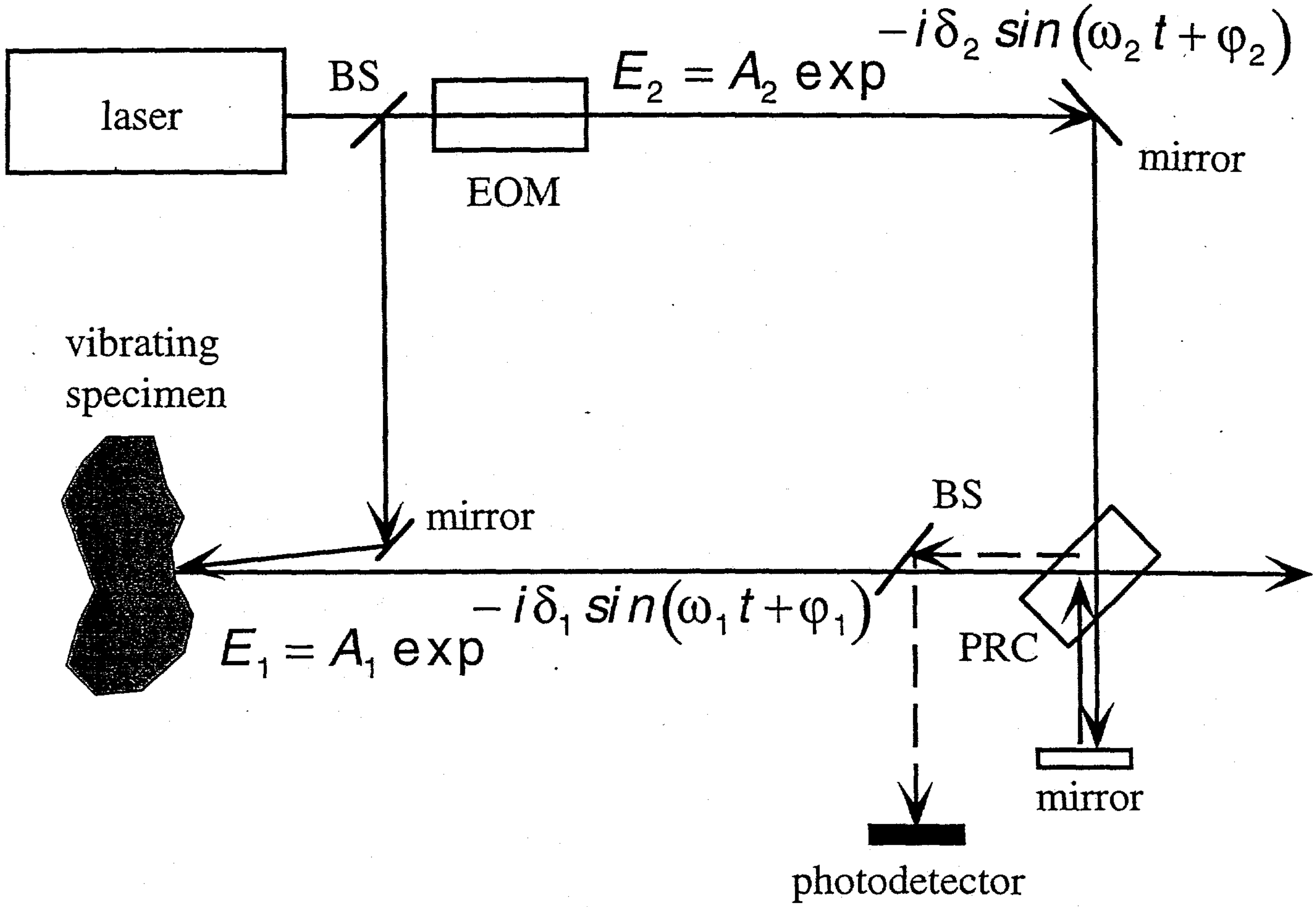

FIG. 1 - Experimental setup for all-optical processing using photorefractive four-wave mixing. PRC: photorefractive crystal; BS: beamsplitter; E_1 and E_2: frequency modulated object and reference beams, respectively.

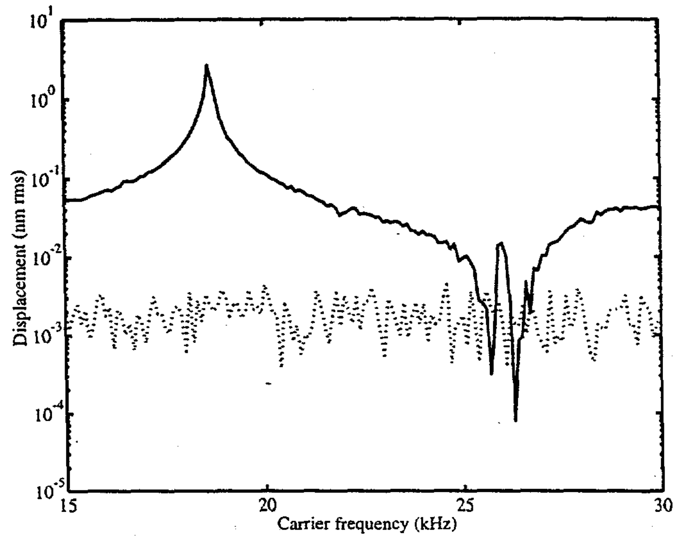

FIG. 2 - The amplitude spectrum of a vibrating surface showing the fundamental resonance and noise level.

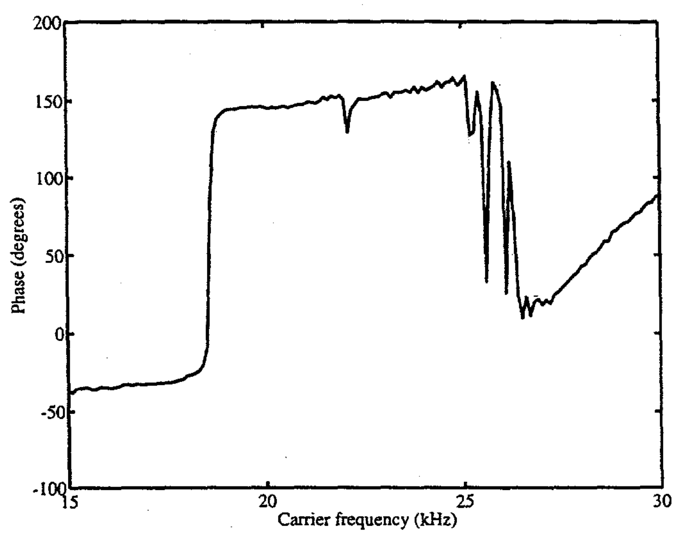

FIG. 3 - The corresponding phase spectrum.

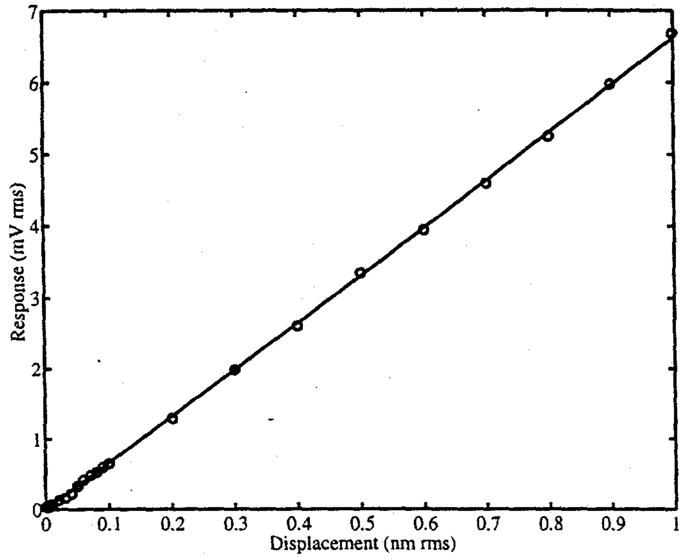

FIG. 4 - Linear response of the wave mixing process versus specimen displacement, δ_1. Reference modulation amplitude δ_2 was fixed at 1.1 radians.

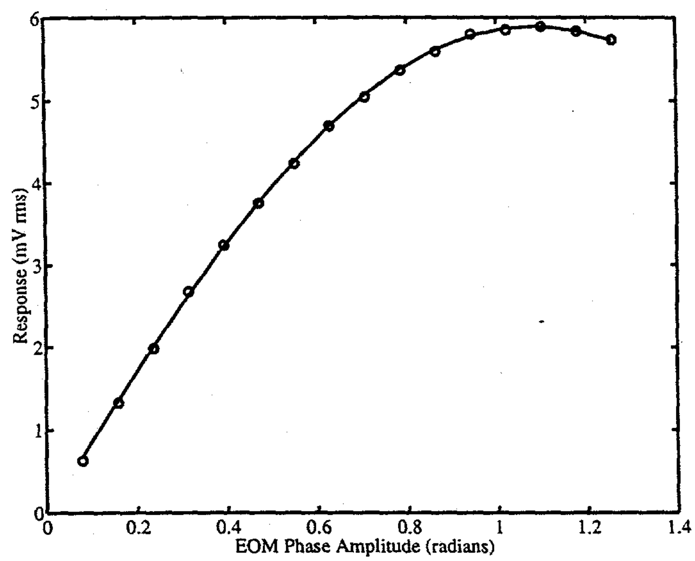

FIG. 5 - The effect of reference EOM amplitude, δ_2, on the wave mixing process. Solid line is equation (1), peak occurs at 1.1 radians. Specimen displacement was fixed at $\xi_1 = .15$ nm rms.

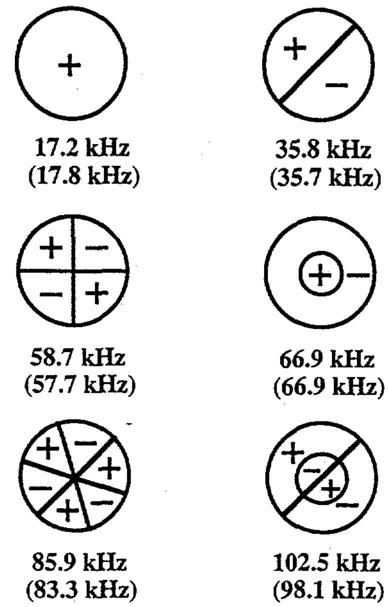

FIG. 6 - First (top left, second top right, etc) through sixth mode (bottom right) shapes for a rigidly clamped disc. Plus signs (+) and minus signs (-) denote regions of positive phase relative to regions of negative phase. Resonant frequencies are given for each mode shape, experimentally determined values are shown in parentheses.

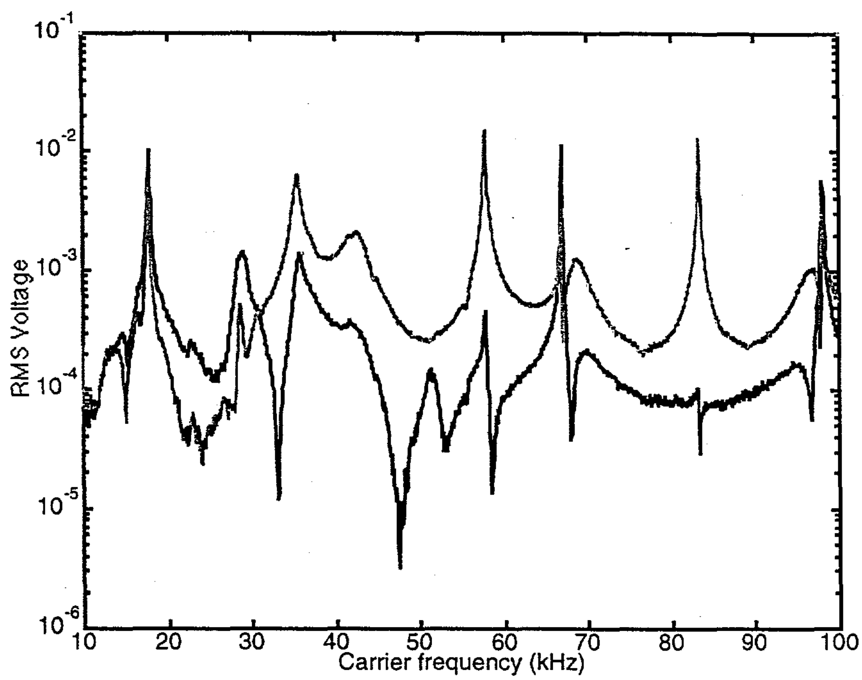

FIG. 7 - Comparison of theoretical eigenfrequencies (circles) with those determined experimentally (lines). First six resonant vibrational modes were detected between 10 kHz and 100 kHz, sixth theoretical mode being just beyond 100 kHz. Solid and dashed lines are swept frequency scans taken with the probing beam positioned at the center and just off-center of the specimen, respectively.