High sensitivity pulsed laser vibrometer and its application as a laser microphone

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We experimentally demonstrate a high sensitivity pulsed laser vibrometer that is capable of detecting optically rough surfaces vibrating with the displacement value of 75 pm as well as its application as a laser microphone. By directing the probe light beam repeatedly onto the vibrating diaphragm and/or pressure sensing interface, the sensitivity of the pulsed laser vibrometer in detecting the displacement of the vibrating diaphragm is significantly improved down to an estimated value of less than 4 pm. In this paper, we present the principles of operation of this new kind of laser microphone together with experimental validations. © 2009 American Institute of Physics. [DOI: 10.1063/1.3078520]

Vibrometry is a versatile field with far-flung applications ranging from the detection of buried landmines1 and monitoring of the health conditions of machinery and mechanical components2 to the gentle patting and sounding of watermelons to determine their water content.3 Also of interest is the detection of targeted molecules and chemical compounds using photoacoustic means in which acoustic signatures emitted by the targeted species are detected by a microphone-like device in order to determine their presence and corresponding concentrations.4 By using laser vibrometers to detect surface vibrations, laser vibrometry offers the additional advantage of achieving these goals in a remote and noncontact manner. Conventional laser vibrometers are generally based on optical interferometers, e.g., Michelson interferometers, which unfortunately suffer from their intolerance to the presence of speckles in the light beams5 that leads to the sudden drop-off in output readings and hence erroneous interpretation of the surface vibration conditions being monitored. Even more challenging is the fact that significantly improved sensitivity in surface displacement detection down to subpicometer range is required in certain applications, including photoacoustic detection of targeted molecules with standoff distances in the range of tens of meters.

By using continuous-wave light sources and lock-in detection, photo-EMF sensors were previously showed to detect vibrations of mirrorlike surfaces with displacements as small as a few picometers (10^-12 m), while for optically rough surfaces, displacements greater than 100 pm were also detected.6 The deployment of lock-in detection, however, requires the knowledge of the supposedly unknown vibration frequencies of the surface under surveillance and is thus unsuitable for applications in which the target’s vibration conditions are entirely unknown. As a contrast, we recently demonstrated a pulsed laser vibrometer based on the combination of photo-EMF sensors and pulsed light sources.7 The spectrum of the vibrating surface can be derived by performing fast Fourier transform calculations on the photo-EMF sensor output photocurrents, without requiring any prior knowledge on the conditions of the unknown target being monitored. While surface vibrations with the displacement of 250 nm were identified previously,7 we present here further improvements in the detection sensitivity of the photo-EMF pulsed laser vibrometer (PPLV). In particular, we demonstrate the real-time identification of surface vibrations with displacements as small as 75 pm from an optically rough aluminum surface with the modest average optical power density of roughly 100 nW/mm^2 at the photosensor. For applications such as the standoff detection of explosives using laser photoacoustic spectroscopy, we also devise a new kind of laser microphone based on PPLV that is capable of detecting surface vibrations with displacements smaller than an estimated value of 4 pm. Theoretical modeling and experimental validations of the PPLV laser microphone are also presented.

Under typical experimental conditions, the photo-EMF sensors produce photocurrent density j(t) that can be approximated as8

\[
\frac{d^2 j}{dt^2}(t) = \kappa \phi(t) \times P_{\text{probe}}(t),
\]

where \(P_{\text{probe}}(t)\) is the probe beam power density arriving at the sensor, \(\phi(t)\) is the temporal phase modulation it suffers from the vibrating surface, and \(\kappa\) is a constant determined by the geometric arrangement of the light beams, sensor material characteristics, and photon energy, as well as the reference light beam intensity. The high power density found in the laser pulses (e.g., Q-switched pulses), albeit only short-lived, increases significantly the photocurrent generated by the photo-EMF sensor, according to Eq. (1), thus leading to discrete samples/readings of the analog surface vibration with better signal-to-noise ratios than those that can be achieved by continuous-wave light sources with comparable average power levels. These discrete samples can be used to reconstruct in real-time the underlying analog surface vibrations, provided that the vibration frequencies do not exceed the Nyquist sampling rate.9 Furthermore, the fact that the signal photocurrent strength is proportional to the total amount of phase shift imposed on the probe light beam by
the vibrating surface also suggests that when configured as a laser microphone, the PPLVs output signal strength can be further enhanced by repeatedly bouncing the probe light beam onto the vibrating surface, effectively amplifying the total amount of phase modulation imposed onto the probe beam. Figure 1 shows one embodiment of the PPLV laser microphone in which the pulsed light source output is split into the reference and probe light beams. The reference beam impinges onto the photo-EMF sensor directly while the probe light beam is directed onto the vibrating surface and/or diaphragm. Displaced slightly away is the reflective mirror assisting the probe light beam in achieving multiple bounces onto the diaphragm. Upon its final exit from the diaphragm-reflective-mirror assembly, the probe light beam is directed onto the photo-EMF sensor. Note that by removing the reflective mirror, the PPLV laser microphone shown in Fig. 1 degenerates back into the usual form of a PPLV laser vibrometer.

For simplicity it is assumed that the vibrating surface/diaphragm is being agitated by a sinusoidal signal of $d \sin(\omega t)$, where $\omega$ is the angular frequency of vibration and $d$ is the maximal displacement of the diaphragm. The amount of phase modulation imposed onto the probe light beam upon its one bounce from the diaphragm is then given by

$$\phi_0(t) = 4\pi d \sin(\omega t) / \lambda,$$

where $\lambda$ is the wavelength of the light beam. By repeatedly bouncing the probe light beam onto the diaphragm, it can be shown that the total amount of temporal phase modulation suffered by the probe light beam is given by

$$\phi(t) = \sum_{n=0}^{N-1} d \sin(\omega t + (n-1)\theta) 4\pi / \lambda,$$  \hspace{1cm} (2)

where $n = 1, 2, \ldots, N$, with $N$ representing the total number of bounces the probe beam strikes the diaphragm. The phase $\theta = 2\omega L/c$, where $L$ is the separation between the diaphragm and the reflective mirror and $c$ is the speed of light, is the additional phase delay experienced by the probe light beam in sensing the vibrating diaphragm upon its round-trip passage between the diaphragm and the reflective mirror. Other static phase delays caused by the additional path length traveled by the probe light beam are not included in Eq. (2) because they do not affect the generation of photocurrents from the photo-EMF sensor. Equation (2) shows that if the additional phase shift $N\theta$ is negligible due, for example, to the limited number of bounces or minimal separation between the diaphragm and the reflective mirror (i.e., $2NL < \delta$ the spatial extent of the laser pulses), the total temporal phase shift suffered by the probe light beam can be approximated by

$$\phi(t) \approx N d \sin(\omega t) 4\pi / \lambda = N\phi_0(t).$$ \hspace{1cm} (3)

Thus, the effective displacement of the vibrating diaphragm is amplified by a factor of $N$ by the $N$-bounce configuration of the PPLV laser microphone whose output photocurrent strength is consequently enhanced by the same factor, as Eq. (1) indicates. In terms of power spectral density, the enhancement in output signal strength is then given by $N^2$. Thermal noise and shot noise of the detection system are not affected by the number of bounces, and it is thus expected that the detection sensitivity of the PPLV laser microphone will be improved accordingly.

A homemade, passively Q-switched neodymium doped yttrium aluminum garnet laser with unstable characteristics (repetition rate of $\sim 1.2-4$ kHz, pulse width of $\sim 20-40$ ns) was used as the light source. The vanadium-doped cadmium telluride (CdTe:V) based photo-EMF sensor was grown by Brimrose. The sensor output photocurrents were converted into voltages for further processing by a transimpedance amplifier with a 100 MHz bandwidth. The PPLV was first used as a typical laser vibrometer (i.e., $N=1$) to monitor one piece of machined aluminum whose surface quality was far from optically flat, as can be seen from the speckled probe beam patterns shown in the inset of Fig. 2. The aluminum was agitated at the frequencies of 600 and 500 Hz, respectively, with the vibration displacement of 75 pm. While the various spurious noise peaks illustrate the abundant background noise level present in our laboratory, Fig. 2 also shows that the PPLV identified the applied surface vibrations with the detected signal peaks elevating from their adjacent noise floor by approximately 10 dB, suggesting that further improvement is likely.

The theoretical analysis for the PPLV laser microphone is validated by Fig. 3 which depicts the vibration power spectra of a gold mirror detected, respectively, by a three-, five-, and six-bounce PPLV laser microphone. The mirror...
vibrated sinusoidally with the frequency of 500 Hz and the displacement value of 400 pm. As predicted by Eqs. (1) and (3), Fig. 3 shows that the power spectral peak strength increases in proportion to $N^2$. Figure 3 also suggests that even greater enhancement in signal strength appears likely if the PPLV laser microphone can support more iterations of bounces. Indeed, Fig. 4 shows the vibration power spectra detected by a PPLV laser microphone with an estimated 23 bounces. Even though the mirror’s vibration displacement value was only 40 pm, the spectral peaks shown in Fig. 4 exhibit excellent signal-to-noise ratios, indicating that the 23-bounce PPLV laser microphone can detect much smaller surface displacements. If we define the minimal detectable surface displacement as the value at which the signal peak strength is comparable to its adjacent noise floor, the inset of Fig. 4 would suggest that the 23-bounce PPLV laser microphone can sense displacement values smaller than 4 pm under the conditions described in Fig. 4.

In conclusion, by using the PPLV we have demonstrated the real-time detection of optical speckle-inducing surfaces vibrating with displacements as small as 75 pm, while displacement values estimated to be smaller than 4 pm can also be detected when the PPLV is configured as a multiple-bounce laser microphone. The PPLV is highly tolerant in the presence of optical speckles and does not suffer from the signal drop-offs faced by conventional optical interferometer-based laser vibrometers. The demonstrated detection sensitivity paves the way for using the PPLV laser microphone in a number of highly sensitive applications.

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