Multipoint laser Doppler vibrometry using holographic optical elements and a CMOS digital camera

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A laser Doppler vibrometer (LDV) is described in which holographic optical elements are used to provide the interferometer reference and object illumination beams. A complementary metal-oxide semiconductor camera, incorporating a digital signal processor, is used to carry out real-time signal processing of the interferometer output to allow multipoint LDV to be implemented. © 2008 Optical Society of America

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In laser Doppler vibrometry (LDV) a laser beam backscattered from a vibrating test object, and therefore Doppler shifted in frequency, is mixed with a reference beam at a photodetector. This generates a beat frequency whose value depends on the velocity of the object at the point of illumination [1]. Directional sensitivity is obtained by shifting the transmitted laser frequency by acousto-optic modulation [2] or modulation of the drive current in a laser diode [3]. Scanning LDV [1] uses mirrors to direct the laser beam to any specified location on the object. These have to move very quickly and precisely, and their orientations have to be precisely specified to the data-acquisition system. A simpler alternate scheme can be implemented in which the object is continuously and entirely illuminated and a complementary metal-oxide semiconductor (CMOS) camera (AKAtech iMVS-135) with an on-board digital signal processor (DSP) is employed [4,5]. The camera features random region-of-interest pixel access in space and time at fast frame rates. In this way multipoint LDV can be implemented, as each pixel corresponds to a single point on the object. A reflection holographic optical element (RHOE) effectively provides the reference beam in the interferometer [6]. A transmissive HOE (THOE) is also employed to ensure on-axis illumination and imaging of the object so that the system is sensitive only to out-of-plane motion. Synthetic heterodyne demodulation was used to retrieve a phase-modulated signal caused by a vibrating object modulating the path difference in the interferometer.

The RHOE was recorded in Integraf PFG-03M silver halide holographic emulsion, on glass substrate (63 mm $\times$ 63 mm), using a 633 nm He–Ne laser, as shown in Fig. 1. The object is a flat diffusely reflecting surface so that, on reconstruction, a diffuse or speckled beam of laser light is produced to act as a reference beam in the interferometer. The light intensity and exposure time were 200 μW/cm^2 and 10 s, respectively. JD-4 [7] processing was used. The diffraction efficiency, defined as the ratio of the diffracted and incident light intensities, was 50%. A THOE in the form of a diffraction grating 5 cm $\times$ 5 cm and diffraction efficiency of 85% was recorded in acrylamide photopolymer [8,9] with a 532 nm laser using the arrangement shown in Fig. 2 using a total intensity of 6 mW cm^{-2} and an exposure time of 15 s. This THOE provides illumination of the object along the normal to its surface, as well as allowing for imaging along the normal, so that the system is sensitive only to out-of-plane motion of the object.

The LDV system is schematically shown in Fig. 3. The laser light is spatially filtered and collimated and illuminates the RHOE and THOE. The RHOE reconstructs the beam of light, originally scattered from a diffusely reflecting surface, to act as a reference beam. The RHOE efficiency of 50% allows the transmission of the remaining incident light, 85% of which is diffracted into the first order by the THOE. The object under test is a metal disk mounted on a piezoelectric transducer driven by a sinusoidal varying voltage. The reflected light from the object is efficiently transmitted through the two HOEs, being now off-Bragg, and interferes with the reference beam at the CMOS camera. To evaluate the quality of the signal from the interferometer, a lens with an adjustable iris diaphragm was used to image the object

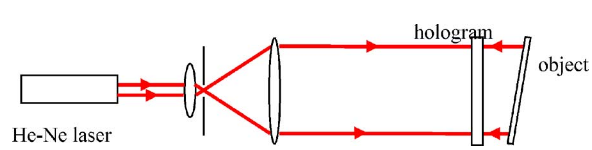

Fig. 1. (Color online) Recording a RHOE.

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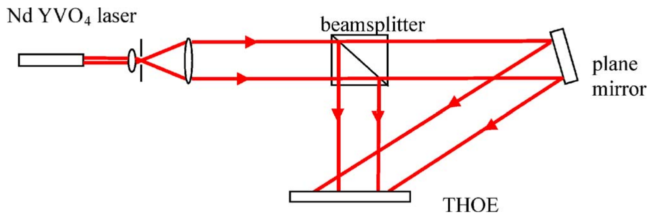

Fig. 2. (Color online) Recording a THOE.

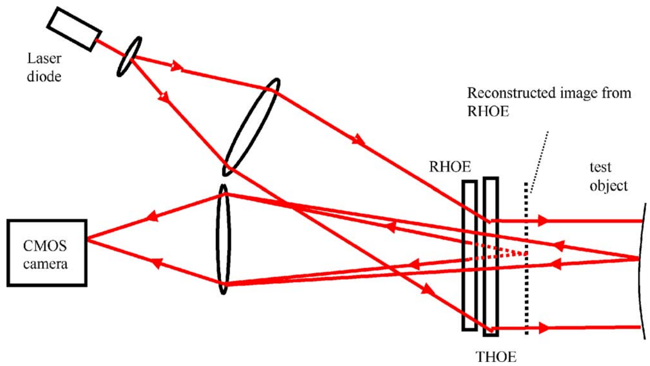

Fig. 3. (Color online) LDV system.

onto a pinhole of diameter 25 μm placed in front of a photomultiplier tube (PMT, type IP28A); a typical result is shown in Fig. 4. The modulation depth was 25%, but this figure is not optimal, as the lens aperture needed to be quite large in order to obtain a signal so that the speckle size was not matched to the aperture of the PMT. The light from the interferometer was detected by the CMOS camera for processing to retrieve the vibration signal.

The sensitivity of an interferometer-based displacement/vibration detection system is dependent on the ambient conditions. If the refractive index of the interferometer cavity changes owing to slowly varying ambient conditions, such as temperature, then the sensitivity will drift. The sensitivity is a maximum when the interferometer is in quadrature and a minimum when it is out of quadrature. This problem can be overcome through the use of synthetic heterodyne demodulation [10]. The technique involves the synthesis of a heterodyne signal from an induced phase modulation. The phase modulation can be generated through suitable sinusoidal modulation of the laser frequency. In the case of a diode laser, this can be achieved by small-signal modulation of the laser current. The modulation frequency is chosen such that it is much larger than the frequency of the vibration signal of interest. The resulting synthetic heterodyne signal will contain harmonics at integer multiples of the laser modulation frequency. The sidebands of the harmonics contain the vibration signal of interest. The first two harmonics and associated sidebands can be combined by a process of differentiation and cross-multiplication to obtain an output signal proportional to the original vibration signal, which is not affected by interferometer drift. In the experiment, the current driving a 650 nm laser diode was sinusoidally modulated at 1 kHz. The synthetic heterodyne technique was implemented in real time on the camera DSP. The camera with customized software for subsequent analysis and display of the retrieved vibration signal was interfaced to a computer providing control of the software. The camera was focused on to the object to obtain a sharp image that was displayed on a computer monitor. Individual camera pixels with good amplitude modulation were selected and analyzed. An example of the power spectrum of a successfully retrieved vibration signal is shown in Fig. 5. Vibration frequencies of up to 100 Hz were successfully retrieved. Some instability was experienced, because the side-mode rejection ratio of the Fabry–Perot laser was only approximately 7 dB. In addition, although the laser temperature was carefully controlled, the laser was still prone to mode hopping. A much-improved performance would be expected from a single-wavelength laser, such as a distributed feedback laser.

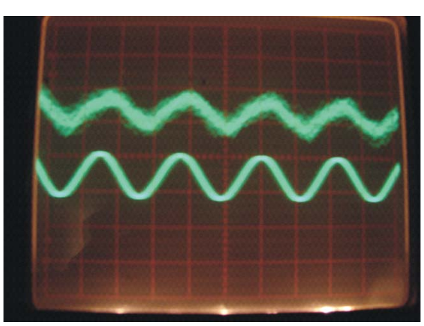

Fig. 4. (Color online) 2.22 kHz interferometer signal (upper trace) and drive signal (lower trace).

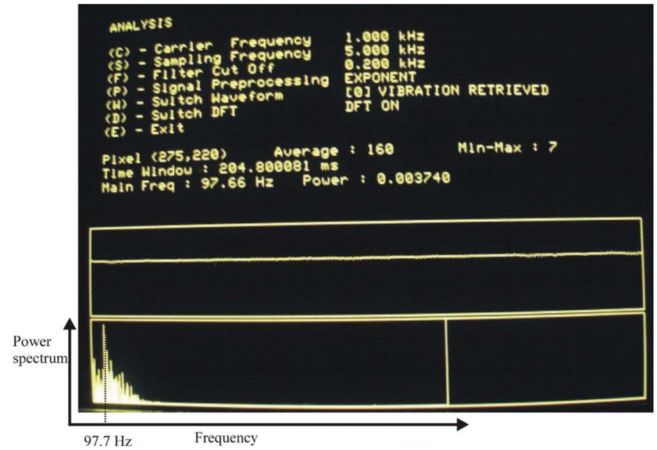

Fig. 5. (Color online) Customized software showing the demodulation algorithm settings and the retrieved 100 Hz vibration power spectrum at a single pixel corresponding to a particular point on the vibrating object. Because of the limited frequency resolution of the signal processing, the detected frequency is 97.7 Hz.

A simple out-of-plane multipoint LDV system incorporating HOEs and a CMOS DSP camera was shown to be able to detect vibration signals at frequencies up to 100 Hz from a vibrating surface. The CMOS DSP camera allows for random pixel access, thereby enabling the user to examine particular regions of interest on the vibrating surface.

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