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Spatially encoded multibeam laser Doppler vibrometry using a single photodetector

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A laser Doppler vibrometer with single photodetector is introduced to measure the vibration on multiple points of target simultaneously. A 2×5 beam array with various frequency shifts is generated by three acousto-optic devices, illuminating different points on a vibrating object. The reflected beams interfere with a reference beam on a high-speed photodetector, and the signal is amplified and digitized with a rate of 500 megasamples/s. To extract vibration information of different points, the carrier frequencies of each beam are elaborately designed so that they can be separated from cross-talk regions in the spectrum. The experimental results are compared with that from a commercial single-point vibrometer, and the comparison shows that it is possible to do a precise measurement on multiple points simultaneously using a single photodetector. © 2010 Optical Society of America
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Laser Doppler vibrometry (LDV) [1] is a well-known technique to measure the motions, vibrations, and mode shapes of structures and machine components. Compared with a full-field measurement by high-speed-camera-based laser interferometry [2,3], photodetector-based LDV can offer only a pointwise measurement. However, it is possible to scan the laser beam to build up a vibrometric image [4]. These scanning laser Doppler vibrometers (SLDV) assume that the measurement conditions remain invariant while multiple and identical, sequential measurements are performed. This assumption makes SLDVs impractical to measure transient events. In recent years, several types of multichannel and multipoint [5] LDVs have been reported; this novel idea first appeared in 1998 [6]. Now it has evolved into prototype [7] and custom-designed products [8]. However, such multipoint versions are normally a combination of several sets of single-point vibrometers [9] or use multiple detectors or detector arrays [7–11], which increases the complexity of the system and results in a prohibitive price. High-frequency photodetectors and high-speed digitizers are widely available with a sampling rate of >10 gigasamples/s. Sufficient frequency range is available to encode vibration signals on separated points into different frequency bands. In this Letter, we present spatially encoded multibeam vibrometry using a single photodetector.

Among various types of LDVs, the most common configuration is the heterodyne interferometer, where an optical frequency shift is introduced into one arm of the interferometer to obtain a virtual velocity offset. The intensity at the detector can be expressed as

$$I(t) = A_0 + A_m \cos[2\pi(f_B + f_D(t))t + \varphi_0], \quad (1)$$

where A_0 and A_m are the intensity bias and modulation factor, respectively. φ_0 is an initial phase. f_B is a constant frequency shift introduced by the acousto-

optic device. $f_D(t) = \{[V(t)S]/\lambda\}$ is the Doppler frequency shift, which is determined by the object velocity $V(t)$ and the wavelength λ of the light source. S is the sensitivity vector given by the geometry of setup. $S=2$ when the illumination and observation are approximately coaxial to the vibration direction.

In the proposed spatially encoded multibeam LDV, a 2×5 beam array with various frequency shifts is generated by three acousto-optic devices: The first is an optical frequency shifter in the Raman–Nath regime (Brimrose, AMF-20-1550, separation angle = 12 mrad, rf power tunable) to generate a beam array of five diffraction orders ($-2, -1, 0, +1, +2$) in the x direction with a frequency shift of $f_{RN}=20$ MHz in between [Fig. 1(a)]. The second is an optical frequency shifter in the Bragg regime (Brimrose, AMF-100-1550, separation angle = 62 mrad, rf power

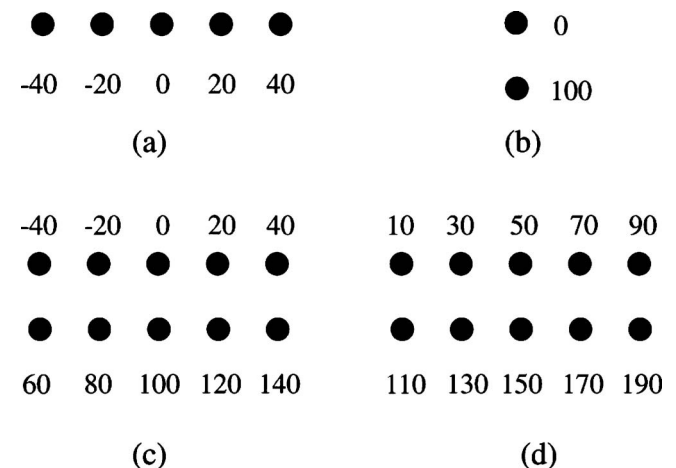


Fig. 1. Beam array with different frequency shifts generated by (a) Raman–Nath frequency shifter, (b) frequency shifter in Bragg regime, and (c) combination of (a) and (b). (d) Final frequency shifts of beam array after a 50 MHz fiber-based acousto-optic modulator (AOM) is introduced (all frequency shift values are in megahertz).

tunable) to generate a two-beam array of 0 and +1 diffraction order in the y direction with a frequency shift of $f_{\text{Bragg}} = 5f_{\text{RN}} = 100$ MHz [Fig. 1(b)]. Using a telescope system [Fig. 2(a)], these two devices can generate a 2×5 beam array with frequency shifts as shown in Fig. 1(c). The width–height ratio of the beam array is determined by the focal lengths of the lenses in the telescope system. To ensure the feasibility of spectrum analysis, we separate the measurement signals from the cross-talk regions by using a 50 MHz fiber-based AOM before the Raman–Nath frequency shifter. The frequency shift amount is calculated by $2f_{\text{RN}} + 0.5f_{\text{RN}}$. The first term is to shift the negative frequencies to positive, while the second term is to separate the signal frequencies from the cross-talk regions. Fig. 1(d) shows the final frequency shifts of the beam array. This beam array will be projected on a vibration object, and the reflected beams will interfere with a reference beam. Assuming that the Doppler frequency shift on each point is ± 3.3 MHz (equivalent to ± 2.55 m/s in velocity when a 1550 nm laser is used), the vibration signals on different carriers are limited in the spectrum regions of

10 ± 3.3 MHz, 30 ± 3.3 MHz, ..., 190 ± 3.3 MHz, and the cross-talk region among ten object beams is limited to 20 ± 6.6 MHz, 40 ± 6.6 MHz, ..., 180 ± 6.6 MHz [Fig. 3(a)]. With this configuration, the vibration signal on different points can be retrieved using conventional Fourier analysis.

Figure 2(a) shows the experimental setup of the proposed multibeam laser Doppler vibrometer. A linearly polarized laser beam from a DFB laser system (Photonik, 80 mW, $\lambda = 1548.53$ nm) is split into a reference beam and an object beam by a 1:99 single-mode-fiber coupler, before the frequency of object beam is shifted by a fiber-based AOM (Brimrose, AMF-50-1550-2FP+). The object beam is collimated by a GRIN lens and split into a 2×5 beam array by the frequency-shifting system mentioned above. The collimated beam array then passes through a polarizing beam splitter (PBS) and a quarter-wave plate and illuminates the testing object with a retroreflective tape. The polarization of the beam array can be changed by a polarization controller so that most of the power can pass through the PBS. The testing object is a pair of cantilever beams with different thicknesses [Fig. 2(b)] and excited by a shaker system whose frequency is controlled by a function generator. The reflected beam array is directed to another

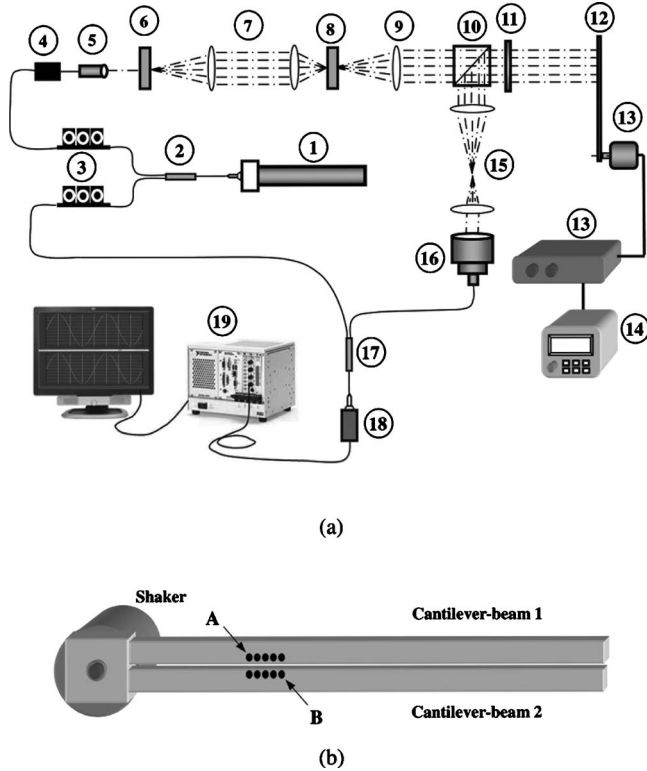


Fig. 2. (a) Experimental setup of multibeam LDV with a single detector: 1, 80 mW distributed feedback (DFB) laser system; 2, single-mode-fiber coupler (1:99); 3, polarization controller; 4, fiber-based acousto-optic modulator; 5, gradient-index lens; 6, Raman–Nath frequency shifter; 7, telescope system that determines the width–height ratio of the beam array; 8, Bragg frequency shifter; 9, collimating lens; 10, polarizing beam splitter; 11, quarter-wave plate; 12, specimen; 13, shaker system; 14, function generator; 15, telescope system to reduce the size of beam array; 16, collimating lens; 17, single-mode-fiber coupler (50:50); 18, high-speed photodetector; 19, NI preamplifier and high-speed digitizer with processor. (b) Specimen: two cantilever beams with different thickness.

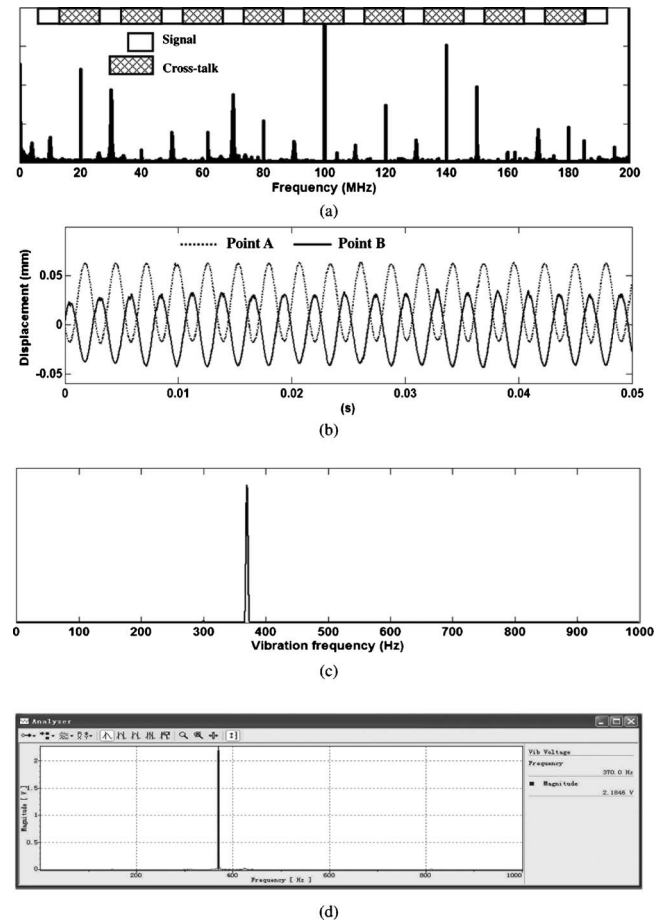


Fig. 3. (a) spectrum of the signal; (b) retrieved displacement of points A and B; (c) spectrum of displacement of point A obtained by proposed method; (d) spectrum of displacement of point A obtained by Polytec PDV-100 single-point vibrometer.

telescope system to reduce the size so that it can be received by a fiber-based collimation lens (Thorlabs, F240FC-1550, $NA_{\text{lens}}=0.50$, $f=8.0$ mm). The object beams then interfered with a reference beam whose polarization is also adjusted to maximize the magnitude of the beating signal. The interference signal received by a high-speed Indium Gallium Arsenide (InGaAs) photodetector (Thorlabs DET01CFC, 2 GHz) is amplified by a PXI pre-amplifier (National Instruments, PXI-5690, max. 30 dB) and digitized by a high-speed A-D card (NI, PXI-5154, 8-bit, 2 GS/s) with a rate of five hundred million sampling points per second.

Figure 3(a) shows the frequency spectrum of the recorded signal obtained by Fourier transform (FT). Bandpass filters at different frequency ranges, inverse-FT and carrier removal, are then processed to obtain the phase variation that is proportional to the displacement of different points. Figure 3(b) shows the displacements of points A and B, as indicated in Fig. 2(b). Opposite phase variations are observed owing to the different vibration mode shape of two cantilever beams. Figure 3(c) shows the spectrum of vibration on point A. The result is verified by a commercial single-point vibrometer (Polytec, PDV-100) on point A [Fig. 3(d)]. A frequency peak is found at 370 Hz, the same as that from the proposed method. The displacement profiles of these two cantilever beams at different instants (Fig. 4) indicate the simultaneous vibration measurement on ten points.

It is worth noting that the intensity of the five-beam array generated by the Raman–Nath frequency shifter is normally nonuniform. The power ratio in our experiment is 1.0:9.0:4.8:9.1:1.2. However, this nonuniformity will not seriously affect the measurement, as the signal-to-noise ratio (SNR) is still >10 dB on the first beam. The sensitivity and accuracy of the system depend on the SNR of the beams with the lowest power. From a signal-processing

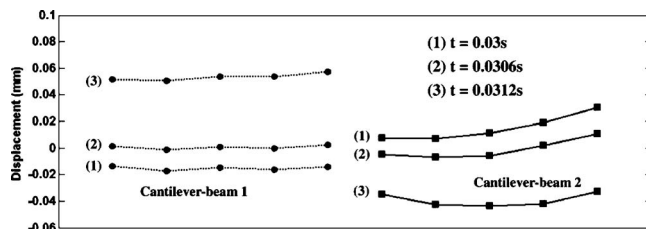


Fig. 4. Displacement of two cantilever beams at different instants.

viewpoint, the analog decoder is still the fastest solution at this stage when real-time measurement is required. However, a digital decoder will gain more applications owing to the rapid improvement in the capacity of computers. Compared with conventional Fourier analysis in a digital decoder, temporal-frequency analysis algorithms, such as windowed Fourier analysis [12] and wavelet analysis [3], will take the full advantage of direct extraction of the instantaneous frequency, which is more suitable to the measurement of transient events.

In this Letter, we presented a simultaneous vibration measurement on ten points using one high-speed photodetector in a laboratory setting. Compared to SLDV and multichannel LDV using detector array, the proposed technique has an advantage in simultaneous measurement of transient events with a relative simple setup. It will throw some light on the development of a multipoint LDV, which would gain more applications in many areas. In addition, a similar idea can also be extended to other technologies in laser Doppler metrology [13], such as Velocimetry.

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