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Utilization of Full Spectrum Space in Single-Sensor-Based Optical Dynamic Measurement

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Abstract— In recent years, interferometry-based dynamic measurement has been widely used in industrial area for non-contact measurement of vibration or continuous deformation. In dynamic measurement, the traditional phase extraction method, phase shifting technique, is not easily accomplished with either high-speed camera or single-pixel photo detector. Hence spectrum analysis becomes a predominant method to extract transient phases. Due to the development of high-speed cameras and photo detectors, now it is possible to encode different information at separated positions in spectrum. In this paper, we will present two applications on fully utilizing spectrum space in dynamic measurement. One is a dual-wavelength image-plane digital holography using high-speed camera, and another is a spatially encoded multi-beam laser Doppler vibrometry using a single detector. The former experiment encodes information of two wavelengths at different parts of the spectrum. Two phase maps can be retrieved from one hologram. These two phase maps can generate a new phase distribution with an equivalent wavelength, so that the capturing rate of the camera can be reduced dramatically. The latter application encodes vibration information of different points on separated frequency ranges. The experiment verifies it is possible to do a precise vibration measurement on a 2×5 matrix simultaneously using a single photo detector. These results show with fully utilization of spectrum space, the capability of optical dynamic measurement will be tremendously improved.

Keywords- vibration measurement; dual-wavelength, Laser Doppler vibrometry, digital holography, spectrum analysis.

I. INTRODUCTION

In the area of optical metrology, interferometry has been applied on dynamic measurement for many years [1]. Generally there are two types of technique with different measurement ranges: (1) High-speed camera based optical interferometry and (2) photo-detector (PD) based laser Doppler vibrometry. Both techniques enjoy the virtues of being noninvasive and high-accuracy, and are getting more widely used by industries. Even in 1990's, the first technique was applied on static or quasi-static measurement because of the limited imaging rate of the CCD camera. However, with the rapid development of high-speed digital recording devices, it is now possible to record interferograms with rates exceeding 100,000 frames per second (fps) and frame size of

1024pixel×1024pixel. Retrieving precise spatial phase maps from these transient interferograms enables measurement of instantaneous 3-D profiles, deformations as well as dynamic responses. Recently, a novel computer-aided optical technology, digital holography [2], has been successfully applied in different types of measurement. The result of the reconstruction of the digital hologram is not only the amplitude of the object, but the phase of the object as well. This advantage makes digital holography more suitable for dynamic measurement. Pedrini [3] described a method for measuring dynamic events in which digital holograms of an object are recorded on a high-speed sensor and the phase of the wavefront recorded at different instants is calculated from the recorded intensity, by use of a 2-D digital Fourier transform method [4]. By unwrapping the phase in the temporal domain it is possible to get the displacement, including the direction of a vibrating object as a function of time. Previous investigation shows a combination of Fourier and windowed Fourier analysis [5-6] can be applied temporally to extract the instantaneous velocity and acceleration of the object [7]. Using this technique, a full-field measurement can be achieved on a vibrating object with low amplitude and/or frequency due to the limited measurement capabilities in time domain.

Compared to a full-field measurement by the technique mentioned above, photo-detector based laser Doppler vibrometry (LDV) [8] can only offer a point-wise measurement, but with large measurement range on vibration amplitude and frequency. On another word, large measurement range on velocity. The LDV is based on the Doppler effect that occurs when the laser light scatter from a moving surface and the interference between the measuring and a reference beam. It allows conversion of the instantaneous velocity of the object into the Doppler frequency shift. For the extraction of the Doppler frequency shift, different interferometric solutions can be used. The heterodyne as Mach-Zehnder and the homodyne as Michelson interferometer are two typical configurations. The main disadvantage of the LDV is that it is impossible to do the measurement simultaneously on different points. This drawback limits the system to study the repeatable events. In recent years, several types of multi-channel and multi-point LDV have been reported. However, such multi-point versions are normally a combination of several sets of single-point vibrometer or use multiple detectors or detector array [9-11],

which increases the complexity of the system and results in a prohibitive price.

Because of the development of high-speed cameras and photo detectors, now it is possible to encode different information at separated positions in spectrum. In this paper, we will present two techniques on fully utilizing spectrum space in dynamic measurement so that the measurement capacities of two above-mentioned methods can be improved. One is a dual-wavelength image-plane digital holography using high-speed camera, and another is a spatially encoded multi-beam laser Doppler vibrometry using a single detector. The former experiment encodes information of two wavelengths at different parts of the spectrum. Two phase maps can be retrieved from one hologram. These two phase maps can generate a new phase distribution with a much larger synthetic wavelength, so that the requirement on capturing rate can be reduced dramatically. The latter application encodes vibration information of different points on separated frequency ranges. A 2×5 beam array with various frequency shifts is generated by three acousto-optic devices, and illuminating different points on a vibrating object. The reflected beams interfere with a reference beam on a high-speed photo-detector, and the signal is amplified and digitized with a rate of 500MS/sec. In order 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 spectrum. The experiment verifies it is possible to do a precise vibration measurement on a 2×5 matrix simultaneously using a single photo detector. These two applications show with fully utilization of spectrum space, the capability of optical dynamic measurement will be tremendously improved.

Figure 1. Schematic layout of the dual-wavelength image-plane digital holography for dynamic measurement

II. DUAL-WAVELENGTH DIGITAL HOLOGRAPHY

A. Principle

A schematic layout of an image-plane digital holography configuration, sensitive to out-of-plane displacement, is shown in Fig. 1. Two lasers with different wavelengths are used. Light

from the first laser is split into an object beam and a reference beam. This object beam illuminates a vibrating specimen with a diffuse surface along a direction e_{11} . Some light is scattered in the observation direction e_o where an image-plane hologram is formed on the CCD sensor, as a result of the interference between the reference beam and the object beam. An aperture is put immediately behind the imaging lens to limit the spatial frequencies of the interference pattern. Similarly a second different laser wavelength is used to generate a second interferogram on the CCD sensor. When these two lasers simultaneously illuminate the object and the detector, the two interferograms will be superimposed on the CCD sensor and one digital hologram containing information about these two interferograms will be obtained. Figure 2(a) shows a typical digital hologram captured by the CCD camera. With a proper selection of the aperture size and a careful adjustment of the two fiber-end positions, it is possible to separate the spectrums of two superimposed holograms in the frequency domain. Figure 2(b) shows the Fourier spectrum of the hologram in Fig. 2(a). The selection of different filtering windows yields two complex amplitudes of the wavefronts $U_1(x, y)$ and $U_2(x, y)$ after the inverse Fourier transform. In our experiment, a series of digital holograms is captured during the vibration of the specimen. Hence, two series of complex amplitudes are obtained with different wavelengths.

Figure 2. (a) Typical digital hologram obtained by illumination from two lasers; (b) spectrum of the digital hologram obtained; (c) typical original wrapped phase map with $\lambda_1 = 633\text{nm}$; (d) typical original wrapped phase map with $\lambda_2 = 523\text{nm}$, and the selected area to process.

In dynamic measurement, the displacement of an object gives a change in the phase of the object beam. The relationship between the phase change $\Delta\phi$ and the out-of-plane displacement z is given by:

$$\Delta\phi = \frac{2\pi}{\lambda} \cdot \mathbf{S} \quad (1)$$

where $\mathbf{S} = \mathbf{e}_i - \mathbf{e}_o$ and $\mathbf{S}$ is the sensitivity vector given by the geometry of the setup, and $\mathbf{e}_i$ and $\mathbf{e}_o$ are the unit vectors of illumination and observation, respectively. For this case, the phase changes at different wavelengths are given by:

$$\Delta\phi_N = 2 \cos\left(\frac{\alpha_N}{2}\right) \frac{2\pi}{\lambda_N} = \frac{2\pi}{\lambda_{eqN}} \quad (2)$$

where $N = 1, 2$; α_1 and α_2 are the angles between the observation direction and the illumination directions with different lasers. $\lambda_{eqN} = \lambda_N / \left(2 \cos\left(\frac{\alpha_N}{2}\right)\right)$ ($N=1, 2$) are the equivalent wavelengths for the out-of-plane displacement measurement when the illumination direction is considered. The phase difference between two digital holograms recorded at instants t_1 and t_m can be calculated by:

$$\Delta\phi_N = \arctan \frac{\text{Im}(U_N(x, y; t_m) \cdot U_N^*(x, y; t_1))}{\text{Re}(U_N(x, y; t_m) \cdot U_N^*(x, y; t_1))} \quad (3)$$

Where $N=1, 2$, Re and Im denote the real and imaginary parts respectively of the complex value. Figures 2(c) and 2(d) show a typical instantaneous phase difference on a vibrating cantilever beam for two different laser wavelengths, respectively. At each instant t_m , a new phase distribution is calculated directly by the subtraction of these two wrapped phases:

$$\Phi = \begin{cases} \Delta\phi_1 - \Delta\phi_2 & \text{if } \Delta\phi_1 \geq \Delta\phi_2 \\ \Delta\phi_1 - \Delta\phi_2 + 2\pi & \text{if } \Delta\phi_1 < \Delta\phi_2 \end{cases} \quad (4)$$

where $0 \leq \Phi < 2\pi$. This phase map is equivalent to a phase distribution of an out-of-plane displacement measurement with a synthetic wavelength Λ , where

$$\Lambda = \frac{\lambda_{eq1} \lambda_{eq2}}{|\lambda_{eq1} - \lambda_{eq2}|} \quad (5)$$

In practice, this phase map contains much more noise than the conventional image-plane digital holography. Normally it is impossible to retrieve the displacement by direct temporal unwrapping. In this application, a windowed Fourier analysis [6] is applied to evaluate the displacement on a vibrating object.

B. Experimental Illustration and Results

Figure 1 shows the experimental setup for the measurements. The specimen tested in this study was a copper cantilever beam with a diffuse surface. A weight is fixed at the free-end of the beam. The distance between the weight and the

clamping end was 80 mm. The width and thickness of the beam were 10 and 0.3mm, respectively. The natural frequency of the beam was around 2 Hz. The first laser used was a He-Ne laser with a power of 15 mW and with a wavelength of $\lambda_1 = 632.8\text{nm}$. The second laser used was a diode-pumped solid state laser (DPSSL, Laser Technologies, Model No. MSL532-20) with a wavelength λ_2 of 532 nm. The cantilever beam was simultaneously illuminated from an angle of $\alpha_1 = 17.9^\circ$ by the He-Ne laser and from an angle of $\alpha_2 = 16.7^\circ$ by the DPSSL. Two single-mode fibers directed the reference beams with different wavelengths toward the CCD sensor from points close to the aperture, and the two interferograms generated by the red and green lasers were superimposed on the camera sensor. The camera used was a PULNIX TM-1001 with an imaging rate of 15 fps, a pixel size of $9.0\mu\text{m} \times 9.0\mu\text{m}$ and a resolution of 992×1018 pixels. In many cases, a calibration of the synthetic wavelength is necessary by shifting an object in z-direction with a known distance and measuring the phase change by the proposed method. In our application, the synthetic wavelength was evaluated as $\Lambda = 3342\text{nm}$.

Figure 3. Series of wrapped phase map obtained by (1) $\lambda_1 = 633\text{nm}$; (2) $\lambda_2 = 523\text{nm}$; (3) phase difference between the result of λ_1 and λ_2 ; (4) wrapped phase map after 2-D Fourier filtering; (5) wrapped phase map after 2-D windowed Fourier filtering.

One hundred and twenty holograms are captured during an eight-second period. Figure 2(b) shows a typical Fourier spectrum of digital holograms captured by the CCD camera. The shadow of the fiber ends can be observed on the spectrums of both digital holograms. When *filtering window A* is selected, the reconstructed phase difference between the two instants represents the out-of-plane displacement for the wavelength 632.8 nm [Fig. 2(c)]. When *filtering window B* is selected, the reconstructed phase between the two instants is the result with wavelength of 532nm [Fig. 2(d)]. A slightly difference can be observed between these two wrapped phase maps. The first two rows of Figure 3 also show series of phase maps with these two wavelengths in a consecutive sequence. Obviously the sampling points in the time axis are not enough, as the phase change between two adjacent frames are sometimes much more than π . However, by subtracting one wrapped phase from another at each instant using (4), a new series of wrapped phases can be obtained as shown in the third row of Fig. 3.

These phase maps represent the out-of-displacement measurement with the synthetic wavelength of 3342nm. The phase difference between the two adjacent frames is within the Nyquist frequency. At each instant, the noise in the wrapped phase map with red and green lasers was different and could not be cancelled in the subtraction. Hence, the noise effect is more serious in the wrapped phase map with the synthetic wavelength. The wrapped phases were then converted to exponential phase signals and filtered by Fourier transform and windowed Fourier transform. The fourth row of Fig. 3 shows the result of 2-D Fourier filtering, while the fifth row shows the results of 2-D windowed Fourier filtering. Figure 4 shows the phase variation of point C [indicated in Fig. 2(d)] after 1-D temporal phase unwrapping. In addition, the spatial distribution of the instantaneous displacement and velocity can also be obtained [12].

Figure 4. Phase variation of point C with the synthetic wavelength of 3342nm.

III. SPATIALLY ENCODED MULTIBEAM LASER DOPPLER VIBROMETRY

A. Principle of Spatially Encoded Multibeam LDV

The most common configuration of LDV 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

$$I(t) = A_0 + A_m \cos [2\pi (f_B + f_D(t))t + \varphi_0] \quad (6)$$

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 acousto-optic device. $f_D(t) = \frac{V(t) \cdot S}{\lambda}$ 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. It equals to two when the illumination and observation are approximately coaxial to the vibration direction.

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

100-1550, separation angle = 62mrad, RF power tunable) to generate a two-beam array of 0 and +1 diffraction order in y-direction with a frequency shift of $f_{Bragg} = 5 \cdot f_{RN} = 100\text{MHz}$ [Fig. 5(b)]. Using a telescope system [Fig.6(a)], these two devices can generate a 2×5 beam array with frequency shifts as shown in Fig. 5(c). The width-height ratio of beam array is determined by the focal lengths of the lenses in the telescope system. (3) To ensure the feasibility of spectrum analysis, we separate the measurement signals from the cross-talk regions using a 50MHz fiber-based acousto-optic modulator (AOM) before the Raman-Nath frequency shifter. The frequency shift amount is calculated by $2 \cdot f_{RN} + 0.5 \cdot f_{RN}$. 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.5(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 the Doppler frequency shift on each point is within the range of $\pm 3.3\text{MHz}$ (equivalent to $\pm 2.55\text{m/s}$ in velocity when a 1550nm laser is used), the vibration signals on different carriers are limited in the spectrum regions of $10 \pm 3.3\text{MHz}$, $30 \pm 3.3\text{MHz}$, ..., $190 \pm 3.3\text{MHz}$, and the cross-talk region among ten object beams are limited in the region of $20 \pm 6.6\text{MHz}$, $40 \pm 6.6\text{MHz}$, ..., $180 \pm 6.6\text{MHz}$. With this configuration, the vibration signal on different points can be retrieved using conventional Fourier analysis.

Figure 5. Beam array with different frequency shifts generated by (a) Raman-Nath frequency shifter; (b) frequency shifter in Bragg regime; (c) Combination of (a) and (b). (d) the final frequency shifts of beam array after a 50MHz fiber-based AOM is introduced (All frequency shift values are with the unit of MHz).

B. Experimental Illustration and Results

Figure 6(a) shows the experimental setup of the proposed multi-beam laser Doppler vibrometer. A linearly-polarized laser beam from a DFB laser system (Photonik, 80mW, $\lambda = 1548.53\text{nm}$) is split into a reference 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 retro-reflective 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-beam with different thickness [Fig. 6(b)] and excited by a shaker system whose frequency is controlled by a function generator. The reflected beam array is directed to another telescope system to reduce the size so that it can be received by a fiber-based collimation lens (Thorlabs, F240FC-1550, $NA_{lens}=0.50$, $f=8.0mm$). 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) photo-detector (Thorlabs DET01CFC, 2GHz) is amplified by a PXI pre-amplifier (National Instruments, PXI-5690, max. 30dB) and digitized by a high-speed A-D card (NI, PXI-5154, 8-bit, 2GS/s) with a rate of five hundred million sampling points per second.

Figure 7 shows the displacements of points A and B as indicated in Fig.6(b). Opposite phase variations are observed due to the different vibration mode shape of two cantilever beams. The displacement profiles of these two cantilever beams at different instants [Fig. (8)] indicate the simultaneous vibration measurement on ten points [13].

Figure 6. (a) Experimental Setup of multi-beam LDV with single detector; 1. 80mW DFB laser system; 2. Single-mode fiber coupler (1:99); 3. Polarization controller; 4. Fiber-based acousto-optic modulator; 5. GRIN lens; 6. Raman-Nath frequency shifter; 7. A telescope system that determines the width-height ratio of 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. A 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) The specimen: two cantilever-beams with different thickness.

Figure 7. Retrieved displacement of points A and B

Figure 8. Displacement of two cantilever beams at different instants

IV. DISCUSSIONS AND CONCLUSIONS

With the development of high-speed cameras and photodetectors, encoding different information at separated spectrum ranges becomes technically possible. The above-mentioned applications are two examples. In the first application, two superimposed digital holograms were captured by one exposure of a single camera. The carriers of these two holograms are designed so that the spectrums of these holograms are separated. Phase maps of two wavelengths are retrieved from one interferogram. These two phase maps will generate a new phase distribution with a synthetic wavelength. This will tremendously increase the measurement range in optical dynamic evaluation, as the velocity measurement capacity is constrained by the Nyquist theorem ----- the maximum phase change between two adjacent interferograms should be less than π , which is equivalent to $\lambda/4$ in out-of-plane displacement measurement. On the other hand, the high-speed photodetector has the frequency band of 40GS/sec. It is broad enough to encode the vibration information of different points at separated bands. In the second application, a single sensor was used to capture a 1-D signal. Compared to multi-detector configuration, the setup is simple and more price-effective. The vibration information of ten points was encoded at different frequency bands. With spectrum analyses, the displacements of ten points on a specimen are measured simultaneously. Compared with scanning LDV or single-point LDV, this technology should be more useful on the measurement of transient events. These two experimental results show the capability of optical dynamic measurement still have room of improvement with the development of sensor and fully utilization of spectrum space.

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