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Dynamic measurement via laser interferometry: crystal growth monitoring and modal parameter analysis

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ABSTRACT

Generally there are two categories of noncontact laser interferometric methods commonly used in dynamic measurement, camera-based full-field interferometry and photo-sensor-based laser Doppler interferometry. The two methods have different advantages and disadvantages thus are suitable for different applications. The camera-based interferometry enjoys the valuable merit of full-field observation and measurement. In this paper, one typical full-field interferometry, digital holography, is employed to monitor the growth process of aqueous sodium chlorate crystals. The phase proportional to the solution concentration is retrieved from the holograms captured by CCD camera in real time. There exist no phase ambiguity problem in holography compared with other optical interferometric methods. On the other hand, laser Doppler interferometry is usually a point-wise measurement but with a very high temporal sampling rate. A multipoint laser Doppler interferometer is proposed for modal parameter measurement in this paper. The multiple transient vibration signals of spatially separated points on a beam structure subjected to a shock excitation are recorded synchronously. The natural frequencies and mode shapes are extracted in the signal processing stage. This paper shows that laser interferometry is able to contribute more to the practical applications in dynamic measurement related fields.

Keywords: dynamic measurement, laser interferometry, digital holographic interferometry, crystal growth, laser Doppler interferometry

1. INTRODUCTION

Laser interferometry is a noncontact and nondestructive metrological method with a high precision. In recent years, with the development of laser, optical communication and computer science, et al, laser interferometric techniques have been widely studied and used in dynamic measurement. The so-called interference of light is a physical phenomenon that two or more light rays overlap to form a resultant light wave of alternating strengthened or weakened intensity distribution in the spatial domain. When one of the parameters in the interferometer alters, light intensity in the same spatial location will change to form a alternating strengthened or weakened distribution in the temporal domain. Interference usually occurs on coherent light waves thus laser rays from the same source are a perfect choice to generate interference for meterage. Generally speaking, there exist two categories of laser interferometric methods, based on the spatial and temporal descriptions of the interference of light, respectively. The former is the full-field interferometry which usually uses camera to record spatial interferograms in succession and realizes a full-field measurement of related physical parameters in the dynamic mechanism through temporal^[1] and spatiotemporal^[2] phase analyses of the interferogram sequence. The latter is photo-sensor-based Laser Doppler Interferometer (LDI), which measures the velocity or displacement in temporal domain by using the laser Doppler effect. The distinct sensor used in each interferometric approach brings forth different advantages and disadvantages.

The camera enjoys the valuable virtue of offering a large number of spatial sampling points, but its temporal sampling rate is still low compared with that of photo sensor. The temporal sampling rate of high-speed camera can reach to over 10^5 frame/s now, but that of photo sensor is 1 GS/s. Considering the constraint of the Nyquist sampling theorem, the camera-based interferometry is unsatisfactory in velocity measurement range. Moreover, the full-field interferometry demands a more powerful laser to illuminate an area, and it is usually implemented in a darkroom as a common commercial camera will respond to both the sunlight and laser light. The LDI commonly measures one or several points and is able to be used in a normal environment with daylight, hence it demands less on lighting conditions.

At present there have been many full-time interferometric methods, such as digital holographic interferometry^[3], Electronic Speckle Pattern Interferometry^[4] and Mach-Zehnder interferometer^[5], etc. Each method has its special properties, but digital holographic interferometry owns some characteristic virtues for dynamic measurement. Firstly, both the amplitude and phase information of the object can be reconstructed using a single hologram, unnecessary to introduce phase shifting or carrier. Secondly, if no carrier is introduced in advance, most of the interferometric methods will suffer from the phase ambiguity problem, that means the phase direction cannot be determined, however, digital holographic interferometry has no such sign indetermination in phase retrieval.

Based on the Doppler effect, many laser Doppler interferometric approaches have been developed, such as Laser Doppler Vibrometer (LDV)^[6], velocimeter^[7] and VISAR (Velocity Interferometer System for Any Reflector)^[8], etc. Although LDI gains above mentioned merits of owning a very high temporal sampling rate and requiring less on lighting condition, its primary demerit that normally only a point-wise measurement can be offered, restricts its use in practice. In order to overcome this problem, the scanning LDI^[9] (SLDI) technique has been developed to measure different spatial points by quickly moving the laser beam on the testing surface. However, scanning is time-consuming thus the SLDI is unsuitable for unsteady phenomena, and the accuracy relies on the stability and repeatability of scanning device which utilizes mirrors to shift the laser beam. Moreover, the asynchronous sampling is more sensitive to noise, since an instantaneous holistic rigid movement of the target or metrical system can be ignored in synchronous sampling, but engenders an evident perturbation in asynchronous sampling.

The full-field interferometry is expected to be more fast, and on the other hand, one of the main developing trends

of LDI is having more measurement points. Besides how to overcome their shortages, how to gain more applications in various investigative and industrial fields is also concerned. For full-field interferometry, the further improvement of high-speed CCD may enhance its sampling rate. Compared with LDI, the full-field technique is more suitable for dynamic measurement which can be done in the darkroom environment and asks for a large number of synchronous spatially separated sampling points. In this paper, digital holographic interferometry is adopted to monitor the crystal growth from solution. The crystallization is a intricate mechanism influenced by many factors hence a non-invasion approach is more suitable for its observation to avoid sensor caused disturbances. The locations where crystals appear are unfeasible to be forecast hence a full-field technique is a better choice. Furthermore, it is a procedure of phase changing hence the digital holographic interferometry is superior in phase analysis since it escapes from the phase ambiguity problem. On the other hand, the wish for increasing synchronous measurement points of LDI demands for new optical designs and signal algorithms not only progresses of hardware. In this paper, a self-synchronized multipoint Laser Doppler Vibrometer (LDV)^[10] is proposed to measure the free vibration of a cantilever beam after a shock excitation on different spatial points. The first three natural frequencies and mode shapes are extracted from the vibration signals.

2. CRYSTAL GROWTH MONITORING

2.1 Principle of Digital Holographic Interferometry

The traditional holography is difficult for real time analysis due to the complicated wet chemical processing and difficult repositioning. Recently, the fast improvement of CCD technology promotes the development of its digital version. CCD is able to continuously capture digital images, which can be analyzed in signal processing stage by a computer, thus the record and reconstruction can be actualized automatically and in real time. According to the way to illuminate the object, the holographic interferometry can be classified as reflection version and transmission version. The former measures the physical parameters of the object surface with the characteristic of diffuse reflection, and the latter is for a transparent media to study the physical parameters related to the optical path change of the media through which the laser beam passed.

A general scheme of transmission digital holographic interferometry is shown in Fig.1. A laser ray is split into two beams. One beam passes through the specimen and is diffused to generate the object wave $O(x', y')$ in the object plane (x', y') . $O(x', y')$ spreads to the hologram plane (x, y) to form a wavefront $O(x, y)$. The other arrives at the hologram plane directly, forms the reference wave $R(x, y)$ and interferes with $O(x, y)$. The interference pattern $H(x, y)$ is called hologram, expressed as Eq.(1):

$$H(x, y) = |O(x, y)|^2 + |R(x, y)|^2 + O(x, y)R^*(x, y) + O^*(x, y)R(x, y) \quad (1)$$

where * denotes the conjugate complex. The hologram is captured by a CCD camera whose sensitive surface is placed at the hologram plane. The object wave can be reconstructed from the hologram by the Fresnel reconstruction algorithm[20-23]. The reconstructed object wave field $U(x', y')$ at the object plane (x', y') at a distance $-d$ from the hologram plane can be expressed as Eq.2:

$$U(x', y') = C \exp\left[\frac{j\pi}{\lambda(-d)}(x'^2 + y'^2)\right] \times FT\{H(x, y)R(x, y) \exp\left[\frac{j\pi}{\lambda(-d)}(x^2 + y^2)\right]\} \quad (2)$$

where FT denotes the two-dimensional Fourier transform and C is a constant. When the specimen varies, a change will be caused in the phase of $O(x, y)$. If two holograms are captured before and after the change, the phase difference between the two states can be calculated by Eq.3:

$$\Delta\varphi = \arctan \frac{\text{Im}(U_2 \cdot U_1^*)}{\text{Re}(U_2 \cdot U_1^*)} \quad (3)$$

The phase difference obtained by Eq.3 is wrapped between $-\pi$ to π , hence a phase unwrapping is needed to get the actual value. If only the phase difference is studied, Eq.2 can be simplified as the Fourier transform of $H(x, y)$ because the other items will be removed automatically in the computation.

Fig.1. A general scheme of transmission digital holography.

For an object with a very small size, a microscope objective (MO) can be added into the setup between the CCD camera and specimen, to form a pre-magnification holographic microscope^[11] to enhance the spatial resolution. The MO will introduce a phase curvature into object wave but it can be removed automatically in Eq.3 if only the phase difference is studied.

2.2 Crystal Growth Monitoring

Large crystals with a high quality are required in many fields especially in biology and medicine related fields. Their shape and quality are affected by many factors, such as concentration, supersaturation, crystal growth rate and mass transfer process, et al. Crystal growth is a very complicated mechanism with lots of problems still needed to be explained and solved. In this case, new experimental techniques for observing the mechanism and measuring the physical parameters will contribute to the related researches. Optical interferometry has been adopted to investigate the crystal growth process for years. In our previous works, Mach-Zehnder interferometer has been employed to study the mass transfer process and the growth rate of crystal growth^[5,12].

Digital holographic interferometry gains particular advantages over other optical methods. In this paper, the crystallization process of NaCl crystal growth by evaporation is monitored in situ by the transmission digital holographic microscope. The crystallization was conducted by evaporation method on 24.24%(w/w) NaCl solution which was prepared with deionized water at 293K, hence the absolute concentration is changing with time. The experimental setup was designed as Fig.1. An assembly of spatial filter and a collimation lens expanded the He-Ne laser ($\lambda=632.8nm$) into a parallel beam with approximately 6mm radius, and then a splitter prism split the beam into two beams. One beam successively passed through the growth cell and a long distance working distance MO (2×) to form a magnified object

wave, and then interfered with another beam served as the reference. A CCD camera was employed to record the holograms in sampling rate of 1 *frame/s* during the crystallization course in 4.45 hours. Figure 2 shows one of the holograms, in the format of 1236×1624 pixels. The original wrapped phase difference between two holograms captured at t_0 and t_n was calculated by Eq.3, and an effective area of 300×580 pixels, where is the growth cell, was selected for further processing. Several phase difference maps are shown in Fig.3. The appearance and growth of two large crystals, on the left bottom and the upper right corner of growth cell, respectively, can be observed evidently.

Fig.2. Hologram recorded at $t_n=14000s$.

Fig.3. Phase difference distribution in the growth cell between $t_0=0s$ and (a) $t_n=4000s$; (b) $t_n=9000s$; (c) $t_n=12000s$; (d) $t_n=14000s$.

Many parameters which are important for analyses of crystal growth can be acquired from the phase information. For instance, the relationship between the phase difference and the change of concentration of solute at pixel coordinates (x, y) can be expressed as:

$$\Delta\varphi(x, y) = \frac{2\pi}{\lambda} \Delta n(x, y) d(x, y) \quad (4)$$

where $\Delta\varphi$ is the phase difference between two instants, Δn is the change of refractive index of solution and d is the

depth of growth cell along the optical path. The relationship between the refractive index and the concentration of NaCl solution measured by WAY-15 ABBE refractometer is $c=5.3899n-7.1852$, hence if the original concentration c_0 at t_0 is known, the concentration c_n at t_n can be calculated by:

$$c_n = 5.3899\Delta n + c_0 \quad (5)$$

The phase variation on the pixel coordinates (295,180) is shown in Fig.4(a). A windowed Fourier filtering^[13] is used to suppress the noise for phase unwrapping, and the filtered wrapped phase and unwrapped phase are shown in Fig.4(b) and Fig.4(c), respectively. The concentration evolution is calculated by Eq.4 and Eq.5 ($d=2mm$), and shown in Fig.4(d).

Fig.4. (a) Temporal variation of original wrapped phase difference between t_n and t_0 on coordinates (295,180); (b) Filtered wrapped phase variation; (c) Unwrapped phase variation; (d) Concentration evolution.

3. MODAL PARAMETERS ANALYSIS

3.1 Principle of the Multipoint LDV

For the same observer, a laser beam will change its frequency when it reflects from a moving target. This phenomenon is called Doppler effect, and the frequency difference f_D is called Doppler frequency shift, linearly related to the velocity of target. LDV measures the velocity and displacement of a moving solid object via detecting the Doppler frequency shift. Heterodyne interferometry is normally adopted in optical design to overcome the problems that the laser frequency is too high to be directly measured and the direction of Doppler shift cannot be determined by current luminous intensity detector. In heterodyne interferometry, usually an Acousto-Optic Modulator (AOM) is employed to introduce an invariable frequency shift f_{AOM} into one arm of the interferometer and thus induce a frequency difference $f_D + f_{AOM}$ between the object beam and reference beam. Compared with laser frequency, $f_D + f_{AOM}$ is extraordinarily small, hence, a beat effect will occur when the two laser beams interferes and thus a photo detector is able to record the intensity fluctuation. Since f_{AOM} is already known, if f_D is in a value within $(-f_{AOM}, +f_{AOM})$, it can be determined in both

the amplitude and direction.

In AOM, there is a general agreement that there are two diffraction types, Bragg diffraction and Raman-Nath diffraction^[14]. These two diffraction types generate different number of diffracted waves, thus a series of multiple laser beams with different f_{AOM} can be produced by a combination of different types of AOMs^[15]. In Bragg diffraction, the observed diffraction pattern generally consists of two diffraction maxima, the zeroth and the first orders. The Raman-Nath diffraction is able to generate several diffracted waves. It occurs at an arbitrary angle of incidence, but the intensity distribution of different orders depends on the incident angle and RF power applied. In certain cases, five orders can be observed, however, in many situations, four orders are observed clearly, and with a fine tuning of incident angle and fine adjustment of RF power, the best intensity ratio of highest power and lowest power is about 2:1, much better than five-order diffraction. Therefore, in the 4-point prototype, it is adopted to generate four diffraction waves.

In this prototype, a laser beam from a single-frequency 1550nm laser system is split into a reference beam and an object beam. The object beam is then connected to a pigtailed AOMs with a 50MHz frequency shift. The output laser beam with a 50MHz frequency shift is then pass through an AOM in the Raman-Nath regime. This AOM generates a beam array of five diffraction orders with a frequency interval of 20MHz. In this application, only four diffraction orders with -20MHz, 0MHz, +20MHz and +40MHz frequency shifts are selected. Figure 5 shows the schematic layout of fiber-based system to split one input laser into four beams with frequency shift of +30MHz, +50MHz, +70MHz and +90MHz. These four laser beams are projected to an object, reflected and interfered with a reference beam. The interference signal detected by the photodetector can be expressed as:

$$I = I_{DC} + \sum_{i=1}^4 I_{M(i)} \cos(2\pi(f_{D(i)} + f_{AOM(i)})t + \Delta\phi_{(i)}) + \sum_{m=1}^3 \sum_{n>m}^4 I_{mn} \cos(2\pi[(f_{D(m)} - f_{D(n)}) + (f_{AOM(m)} - f_{AOM(n)})]t + \Delta\phi_{mn}) \quad (6)$$

where $i=1, 2, 3, 4$; m and n are integers; $f_{AOM(i)}$ are the central frequencies of object beams. The second term is the interference signal between the object beams and reference, from which the useful vibration information of four points can be extracted. The third term is the sum of cross talk between any two object beams, which can be bypassed when the interference signal is processed^[15]. The beam array generated by AOMs is a regular 1-D or 2-D pattern, thus a fiber-based optical design is selected to enhance the flexibility of the system in practical applications^[16].

Fig.5. Schematic layout of fiber-based system to split one input laser into four beams with different frequency shifts.

3.2 Modal Parameter Measurement

Compared with SLDV, the multipoint LDV is more suitable for measurements of unsteady vibrations, due to its synchronization among different sampling points. An experiment is conducted to show this characteristic, as shown in

Fig.6. An aluminium beam of size $270 \times 20 \times 3.1 \text{ mm}$ is clamped at one end. A pendulum is used to apply a shock excitation to the beam at the position of 10 mm to the free end, to make the beam execute a free vibration. The surface off-plane displacement of four sample points A, B, C and D on the central-line of the beam are measured by the proposed 4-point LDV. The demodulation system of the proposed LDV is triggered when the pendulum almost hit the beam.

Fig.6. Experimental layout for the measurement of free vibration of a cantilever beam under a shock load.

Figure 7(a) plots the off-plane displacement distribution of point A in the first 0.14 second after trigger. The off-plane displacement comprises a series of frequency components, thus disturbances can be observed in the waveforms evidently, which indicate the high-frequency components. By using the zoom-FFT algorithm, spectrum of the displacement is calculated, as shown in Fig.7(b). Several resonances can be observed at frequencies of 33.5 Hz , 210.7 Hz and 602.3 Hz , which denote the first three natural frequencies of the cantilever beam.

Fig.7. (a) Off-plane displacement variation of point A in the first 0.14 second after trigger; (b) Spectrum of the displacement.

A band-pass filtering centered on the first natural frequency is conducted on the displacement to extract the corresponding frequency component. The same filtering is conducted to displacement distributions of point B, C and D, and thus the normalized first mode shape can be obtained by reading the off-plane displacement values of the four points at the same time, as shown in Fig.8(a). The experimental result is compared with the simulation by FEM (gray line), as shown in Fig.8(b). Commercial software ANSYS is used to build the cantilever beam model. Material properties of the actual beam, such as the Young's modulus, Poisson ratio and density are tested beforehand and applied to the model. The plane82 8-node quadrilateral element type is chosen. Similarly, the normalized second and third mode shapes are extracted from the temporal signals, compared with the simulative results, and shown in Fig.8(c) and (d), respectively.

The error can be reduced tremendously with the increase of sampling points. At the moment, a 16-point LDV is being developed, and a higher measurement precision can be expected.

Fig.8. (a) Four-point 1st mode shape; (b) Comparison of 1st mode shapes by experiment and by FEM; (c) Comparison of 2nd mode shapes by experiment and by FEM; (d) Comparison of 3rd mode shapes.

4. CONCLUSIONS

Laser interferometry enjoys the merits of being noncontact, nondestructive and high precision, thus attracts more and more interests in dynamic measurement related applications. The two main interferometric methods, full-field interferometry and Doppler interferometry, have different characteristics, virtues and disadvantages. In this paper, one full-field interferometric method, digital holographic interferometry, has been employed to monitor the crystal growth mechanism. It provides a whole observation and phase measurement on the view field of growth cell. No phase ambiguity problem exists in the holographic technique therefore no temporal carrier or other auxiliary approach is needed to help identify the sign of phase. This is a significant advantage of digital holographic interferometry for crystal growth from solution. Compared with full-field interferometry, laser Doppler interferometry is inferior in the number of spatial sampling points. A fiber-based multipoint LDV is described in this paper, which is more suitable for unsteady vibration measurement than conventional single-point or scanning LDV due to its ability of measuring on spatially separated points synchronously. The transient vibration of a cantilever beam has been measured by the multipoint LDV. Via signal processing, the mode shape can be extracted from temporal vibration signals since they are synchronously sampled. At the moment, a 16-point LDV is being developed. With more sampling points, the proposed multipoint LDV is able to gain more applications in dynamic measurement.

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