Vibration measurement of surfaces by structured light projection

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Abstract
In this work a method for out-of-plane vibration measurement using structured light projection is proposed. The light was generated by a Michelson interferometer with a green laser as light source. By illuminating the vibrating surface with straight and parallel interference fringes a jiggling interference pattern is obtained. In order to stabilize the fringe pattern the phase modulation was performed by using a vibrating mirror in the interferometer. We demonstrated the technique by measuring the vibration amplitudes of small objects in the millimeter and submillimeter range.

Keywords: quality control, optical metrology, fringe projection, vibration measurement.
1. Introduction

Optical techniques have been shown along the years to be very effective for vibration measurement (Ostrowsky et al., 1991; Vest, 1979). For instance, Doppler Laser Vibrometry (DLV) is a very well-known optical method used in many applications (Freschi et al., 2000), time average holography and time average digital speckle pattern interferometry (DSPI) allow whole-field analyses and are very suitable for micro-vibration measurements. Variations of those techniques like stroboscopy (Yang et al., 2014) and phase-modulated reference beams (Barbosa, Muramatsu, 1997) allow enlarging the dynamic range of these whole-field techniques. If the vibration amplitudes are too large to be measured by standard time average methods, double-pulse or high-speed camera holography (Pedrini et al., 2006) are also useful tools for this purpose, even enabling the analysis of non-harmonic vibration phenomena. A drawback of holography and DSPI occurs when the points vibrate with the same amplitude, or if the amplitude values do not vary within a interference fringe.

The oblique incidence and projection of structured light is widely used for 3D reconstruction in areas like facial recognition (Guo, 2010), dentistry (Múnera et al., 2012), reverse engineering (Ireland et al., 2008) and microscopy (Yin et al., 2015). The projection of structured light was also used for temporal vibration analyses with the help of a high-speed camera (Guo, 2010) and using Talbot fringes generated by a Ronchi grating projected on an Aluminum cantilever (Rodrigues-Vera et al, 2009). If no high-speed camera is available to synchronize the object vibration with the acquisition rate, there must be another way to stabilize the oscillating projected fringe pattern.

Hence, in order to get stable fringes even with vibrating surfaces a new method of structured light projection for out-of-plane vibration measurement in the millimeter and submillimeter range is proposed. In our experiment, the interference fringes are generated by a Michelson interferometer (MI) in which one of the mirrors is supported by a piezo-electrical transducer in order to phase modulate one of the interfering beams, resulting in a jiggling interference pattern when the illuminated surface does not vibrate. Thus, the interferogram oscillation due to the surface vibration can be compensated by the oscillation caused by the phase modulation of the MI. We obtained a mathematical expression which provides the vibration amplitude of the studied surface as a function of the vibration amplitude of one of the mirrors in the MI.
Vibration amplitude measurements were carried out with a rubber membrane and a formica bar.

2. Vibration analysis by fringe projection

Consider the oblique incidence of a fringe pattern with straight and parallel fringes originated from a Michelson interferometer onto a planar surface. If the angle of incidence is $\theta$, the projected fringe pattern viewed from a direction perpendicular to the surface has a spatial period of $d/\cos \theta$, where $d$ is the interferogram spatial period. Hence, the fringe pattern can be written as

$$I = I_0 \cos^2 \left( \frac{2\pi}{d} \cos \theta x \right),$$

where $x$ is the direction perpendicular to the fringes and $I_0$ is the unmodulated light intensity. The fringe projection for two positions of the vibrating surface with width $X$ is shown in figures 1a and 1b.

If the surface vibrates along the $z$ direction, the fringes will oscillate along the $x$-axis for an observer looking through the $z$-axis. From figure 1b one concludes that a surface displacement $a$ along the $z$-axis corresponds to a maximum lateral fringe displacement of $\Delta x_{\text{max}} = a \tan \theta$ along the $x$-axis with respect to $x = 0$. Hence, a surface vibration given by $a \cos(\omega t)$ produces a lateral displacement $\Delta x_{ob}(t)$ given by

$$\Delta x_{ob}(t) = a \tan \theta \cos(\omega t + \phi_{ob}),$$

where $\phi_{ob}$ is the phase of the vibrating object.

Figure 1. Fringe projection onto the surface a – in the equilibrium position and b – after a displacement $a$
Let us consider now that one of the MI mirrors is supported by a piezoelectric transducer (PZT-M) making the mirror vibrate according to $A_{pzt} \cos(\Omega t + \phi_{pzt})$, where $A_{pzt}$ is the mirror vibration amplitude, $\Omega$ is the vibration frequency and $\phi_{pzt}$ is the phase of the MI vibrating mirror. The time dependent phase shift of this mirror is then $\delta(t) = \left(4\pi A_{pzt}/\lambda\right) \cos(\Omega t + \phi_{pzt})$.

Since a phase shift $\delta$ applied on one of the MI mirrors causes a displacement of $\Delta x = \hat{d} / (2\pi \cos \theta)$ on the fringes projected onto the surface of figure 1a, the fringes oscillate due to this phase shift according to

$$\Delta x_{pzt}(t) = \frac{2d}{\lambda \cos \theta} A_{pzt} \cos(\Omega t + \phi_{pzt})$$

Thus, the total fringe displacement is $\Delta x = \Delta x_{ob} + \Delta x_{pzt}$ due to the simultaneous surface vibration and the MI phase modulation.

The fringe pattern can get static again ($\Delta x = 0$) and its visibility can be somewhat improved provided the object vibration and the MI phase modulation are synchronous, i.e., the conditions below are obeyed:

$$\phi_{pzt} - \phi_{ob} = (2m+1)\pi, \ (m = 0,1,2,...) \tag{3a}$$

$$\omega = \Omega \tag{3b}$$

and

$$\frac{2\pi}{d} a \sin \theta = \frac{4\pi}{\lambda} A_{pzt} \tag{3c}$$

Hence, the from equations (1-3) the vibration amplitude of the surface is written as

$$a = \frac{2d}{\lambda \sin \theta} A_{pzt} \tag{4}$$

Equations (3a) and (3c) determine the conditions for fringe stabilization. By achieving these conditions, both the phase and the vibration amplitude may be determined from equations (3a) and (4), respectively.

3. Experimental setup and results

Figure 2 shows the beam of a 532-nm frequency-doubled diode pumped solid state laser filtered by a spatial filter SF and collimated by a positive lens L1. The beam illuminates the MI to produce interference fringes which illuminate the object after being reflected by folding mirror M. The incidence angle onto the vibrating surface is $\theta = 75^\circ$. One of the mirrors of the
interferometer is slightly misaligned in order to generate the straight parallel fringes and is supported by a home-made piezoelectrical transducer (PZT-M) in order to produce an oscillating interferogram. The analyzed objects are a 50-mm diameter rubber membrane and a 20 x 155 mm² formica bar, all of them attached to and excited by the core of a 18-cm diameter woofer loudspeaker LS driven by one of the outputs of the function generator FG. The ends of the membrane are clamped by a metallic ring. The other FG output is used to excite the PZT-M. Parameters like frequency, drive signal amplitude and phase in both outputs can be set independently from each other. The images are formed by a 480-lines monochrome CCD camera with 30 frames per second. The response of the PZT-M with respect to the vibration amplitude depends on the excitation frequency.

When the object vibrates and the PZT-M is off the fringes covering the object surface appear blurred or completely indistinguishable. By exciting the PZT-M with the same frequency as the object, the fringe visibility starts to enhance as the driving PZT signal is properly adjusted and gets closer to the ideal value. In addition, the phase $\phi_{\text{pzt}}$ must be chosen by properly setting the function generator.

Figure 3a shows a rubber membrane with both the LS and the PZT-M off. The right side of the figure shows the normalized fringe intensity level along the horizontal straight line across points A and B. Figure 3b shows the membrane vibrating at 63 Hz, excited by a 3.210-V amplitude sinusoidal signal and with the PZT-M off. Notice that the membrane vibrates
remarkably at the region surrounded by the dashed circle, where the fringes appear blurred, while at the clamped peripheral part of the membrane the visibility of the fringes remains high. The intensity level shown by the arrow at the right side of the figure confirms the low visibility of the fringes. By adjusting the PZT-M driving voltage amplitude to 1.210 V and its phase to 0.10 rad one obtains an interferogram whose visibility at the membrane center is highest as shown in the interferogram and the intensity level of figure 3c. In this case, due exclusively to the PZT-M vibration the fringe visibility becomes low at the membrane periphery. At the frequency of 63 Hz the PZT-M response is $R_{PZT} = 90$ nm/V, which corresponds to a vibration amplitude of the MI mirror to be $A_{PZT} = R_{PZT} V_{PZT} = 90 \times 1.210 = 108.9$ nm. From figure 3c, one gets $d = 7.0$ mm at the center of the plate, so that the vibration amplitude at the center of the membrane is obtained from equation (4) to be $a = 2.97$ mm.

Figure 3. Vibration of the rubber membrane at 63 Hz for a – unperturbed membrane; b – vibrating membrane and PZT off; c – vibrating membrane and PZT on for $\phi_{PZT} = 0.10$ rad
The vibration measurement of a formica bar is shown in figure 4. Figure 4a shows the unexcited bar with a high-visibility fringe pattern, and figure 4b shows the bar excited by a 60-Hz, \( V_{LS} = 2.700 \, \text{V} \) signal with \( V_{PZT} = 0 \). The blurred fringes surrounded by the high visibility ones evidence that the central-right side of the bar vibrates with maximum amplitude, while the lateral is static.

Figure 4. Vibration of the formica bar at 60 Hz for a – unperturbed bar; b – vibrating bar and PZT off; c – vibrating bar and PZT on for \( \phi_{PZT} = 0.16 \, \text{rad} \)
As the MI is phase modulated such as \( V_{PZT} = 1.400 \text{ V} \) and \( \phi_{PZT} = 0.16 \text{ rad} \), the fringe oscillation due to the object vibration is compensated by the fringe oscillation caused by the phase modulation, as shown in figure 4c, which shows that the fringe visibility became highest at the central-right area and lowest at the lateral parts of the bar. For \( V_{PZT} = 1.400 \text{ V} \) one gets \( A_{PZT} = R_{PZT}V_{PZT} = 90 \times 1.400 = 126 \text{ nm} \), and the vibration amplitude at the center of the bar for \( d = 7.0 \text{ mm} \) according to equation (4) is \( a = 3.4 \text{ mm} \). Moreover, as shown in figures 4b and 4c, by sweeping both the vibration amplitude of the PZT and matching it with the amplitude of the vibrating object, one obtains the amplitude map of the object.

4. Conclusion

A method for vibration measurement based on fringe projection was proposed and discussed. The measurement of vibration amplitudes in the range of millimeters and tenths of millimeters was demonstrated, which is a range that usually cannot be easily performed by other whole-field techniques. Some adjustments difficulties may eventually occur when the object vibration frequency matches the camera acquisition rate. This drawback can be overcome by directly observing the fringes on the surface, without the need of the camera. In this particular case the camera is useful just for image acquisition and storage.

Fringe projection allows scaling the measurement sensitivity by conveniently adjusting the incidence angle. The use of the Michelson interferometer is a very effective experimental solution, since it both produces the structured light and modulates the phase to make the interferogram oscillate. Moreover, it easily allows a convenient change of the spatial period. Differently from other whole-field methods, fringe pattern projection also allows the measurement of surfaces that vibrate as a whole, not requiring the existence of a nodal region. Nevertheless, the proposed method is also able to identify and evaluate regions with different vibration amplitudes.

For the present purpose, the Michelson interferometer can be constructed to be very compact and rugged, in order to operate in somewhat noisy environments without harmful instabilities; moreover, the relatively large measurable amplitudes does enable to perform vibration measurements of objects in such environments, without the requirement of placing them on damped table tops. Those features point out to applications of the technique to perform the testing of vibrating apparatuses and machines in industrial environments.
References


