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Fringe chasing by three-point spatial phase shifting for discrimination of the motion direction in the long-range homodyne laser Doppler vibrometry

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ABSTRACT

In this work, a three-point spatial phase shifting (SPS) method is implemented for chasing of the moving interference fringes in the homodyne laser Doppler vibrometry (HoLDV). By the use of SPS method, we remove disability of the HoLDV in the discrimination of the motion direction for long-range displacements. From the phase increments histogram, phase unwrapping tolerance value is selected, and adequacy of the data acquisition rate and required bandwidth limit are determined. Also in this paper, a detailed investigation on the effect of detectors positioning errors and influence of the Gaussian profile of the interfering beams on the measurements are presented. Performance of the method is verified by measuring a given harmonic vibration produced by a loudspeaker. Also, by the proposed method, vibration of mounting system of a disk laser gain medium is characterized.

1. Introduction

Vibrometry has a special significance in the science and engineering studies. One of the usual optical vibrometry methods is the Homodyne Laser Doppler Vibrometry (HoLDV) [1]. This method employs a two-beam interferometer in which one of the beams is reflected by the vibrating object. In this method, a fringe pattern with a large period is produced and a time-dependent intensity signal is accumulated by a point intensity detector. By changing optical path difference of the interferometer's arms in an interval larger than a quarter of the interfering beams' wavelength, the absolute values of the detectable minimum and maximum intensities are determined. At the equilibrium position of the object, the optical path difference of the interferometer's arms is tuned in such a way the detected signal is the mean value of the absolute minimum and maximum intensities. In this point, known as the quadrature point, the intensity variation due to the object motion is maximum. For small enough values of the object displacements, and at the vicinity of the quadrature point, the response function of the system, defined as the detected intensity against displacement, is linear. For the vibrations with very small values of the amplitudes compared to the interfering beams' wavelength, the intensity signal yields all of the necessary data for the reconstruction of the motion.

In the conventional HoLDV, by increasing the displacement value, the response function of the system gets a sinusoidal form. For a given motion with a maximum displacement larger than a quarter of the wavelength of the interfering beams, after the moment that the detected signal experiences one of the extremum values, determination of the displacement direction is not possible. In other words, in this case, the signal trend does not reflect the direction of the motion and it leads to an ambiguity in the motion reconstruction.

A well-known method for removing the mentioned ambiguity is the use of the heterodyne LDV technique [2]. In this technique a fixed high frequency-shift is applied between the interfering beams, with an order of tens of MHz. Therefore, a fixed-frequency beating is produced even with a non-moving object. Displacement of the object, changes the frequency of the beating. The direction of the displacement is discriminated by the sign of beating frequency change. In this technique, as the beating rates are very high, analog frequency demodulation techniques should be used to extract the vibration characteristics. Another method named pseudo-heterodyne was also used to produce high frequency beating by changing the wavelength of the reference beam [3,4], or by a gradually increasing/decreasing of the reference arm's

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length [5]. Comparing to the HoLDV, implementation of these methods needs more complicated equipment.

It is worth mentioning that by employing quadrature fringe detection method in HoLDV setup, it is possible to overcome to the above-mentioned disability of the HoLDV for discrimination of the motion direction [6–8]. This method can be utilized by using a double polarized laser, a proper combination of polarization beam splitters and quarter-wave plates, and an additional detector in the HoLDV setup. Homodyne interferometry with quadrature fringe detection provides two quadrature signals from the same output source, where their values retrieve the direction of motion and instantaneous position of the vibrating object. The quadrature detection of a Doppler signal has also drawbacks and needs additional hardware, such as a fully stable double polarized laser.

In this work, by the aid of fringe chasing we present a method to determine the direction of motion by HoLDV setup. In comparing with the quadrature fringe detection method, our HoLDV setup is simple and there is no need to the fully stable double polarized laser beam and other additional hardware. For the fringe chasing, we implement a three-point spatial phase shifting (SPS) method and we measure instantaneously the phase of fringe pattern. By this kind of homodyne detection, large-amplitude motions can be easily investigated. In addition, we will show that by the aid of the three-point fringe chasing method, despite of the conventional HoLDV, it is not necessary to tune the system on the quadrature point.

It should be noted that the chasing of the fringes motion can be done by inspection of the successive frames of a movie that is taken from the fringe pattern during the object vibration. Also this can be done by a linear array sensor. In these cases, the sampling rate is decreased due to the low frame/line rates of the recording systems in comparing to the case of three point-detectors. In addition, for high frame/line rates typically over than a 10 kHz rate, these instruments are expensive, volume of the data is huge, and the data transferring processes are time-consuming. On the other hand, for an interference pattern with a sinusoidal profile and known spatial period, knowing the intensities of only three points over a period is enough to calculate the pattern phase. Therefore, apparently the additional data supplied by the 2D or linear array sensors limit the sampling rate. The use of three-point detection remarkably increases sampling rate with respect to the mentioned sensors. For this reason, the proposed three point-detector can be easily extended to the ultrasound regime.

It worth mentioning that, already the N-point SPS method has been used for the detection and compensation of the environmental vibrational noise but the vibration characteristics has not been investigated [9]. Also, in two other works, two different arrangements of the two-point SPS method [10,11], were proposed for the reconstruction of the motion. These arrangements can be only applied when the visibility of fringes is very close to one. Therefore, this condition is not always satisfied. In another work, a similar formulation has also been used to analyze the 2D vibrational modes and the resonant frequencies of a flat speaker [12], where the amplitude of the vibration has been measured, but the temporal behavior has not been recorded.

As the measured phase obtained by implementing SPS method on a HoLDV has a wrapped form, using the phase increments histogram, we present a simple way for selection of the phase unwrapping “tolerance value”. Also, the adequacy of the data acquisition rate and required bandwidth limit are determined from the resulted phase increments histogram of the motion. As the positioning of the detectors at the desired positions accompanies with error, in this work we also present an investigation on the effect of detectors positioning errors on the measurements. Also, the influence of the Gaussian profile of the interfering beams on the results is investigated.

Reliability of the proposed method is examined by simulations of a motion with a constant velocity and a harmonic vibration. Finally, we use the method for detection of vibrations of the mechanical mounting of a thin disk laser gain medium. In the following, formulation of the SPS method in a general form is presented.

2. Homodyne LDV

The HoLDV is based on the two-beam interferometry where one of the beams carries the vibrational information of a single point on the vibrating object via Doppler shift in its wavelength. For a better understanding of the results of the present work, here a brief review on the HoLDV is presented.

For a Michelson type interferometer, the normalized instantaneous intensity is of the form

$$I(t) = 1 + V\cos(2k\Delta L(t)), \tag{1}$$

where $k = 2\pi/\lambda$, is the wavenumber of the reference or probe beam, and $\Delta L(t)$ is the optical path difference (OPD) of the interferometer arms. V is a parameter that specifies contrast of the temporal signal. The OPD can be separated into two parts; the mean OPD, ΔL_0 and a time-varying part corresponding to the vibration, $X(t)$.

For a harmonic vibration $X(t) = A\cos(\Omega t)$ with an angular frequency of Ω and an amplitude of A, the signal of Eq. (1), can be written as

$$I(t) = 1 + V\cos\phi\cos[2kA\cos(\Omega t)] - V\sin\phi\sin[2kA\cos(\Omega t)], \tag{2}$$

where $\phi = 2k\Delta L_0$ is the phase difference between the beams at the equilibrium position of the object. Using the real-valued forms of Jacobi–Anger identities [13]

$$\begin{aligned}\cos(x\cos\theta) &= J_0(x) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(x)\cos(2n\theta),\\ \sin(x\cos\theta) &= -2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(x)\cos[(2n-1)\theta],\end{aligned} \tag{3}$$

where $J_n(x)$ is the first kind Bessel function of order n, Eq. (2) can be rewritten as

$$\begin{aligned}I(t) = 1 + V&\left\{J_0(2kA) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(2kA)\cos(2n\Omega t)\right\}\cos\phi\\ &- V\left\{2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(2kA)\cos[(2n-1)\Omega t]\right\}\sin\phi.\end{aligned} \tag{4}$$

Eq. (4) yields the coefficients of the Fourier series expansion of the HoLDV signal. This means that, despite of the pure harmonic oscillation of the object at a single frequency, there are many higher harmonics in the spectrum of the signal. Higher the amplitude, higher the order of Bessel functions with a noticeable contribution. The contributions of the odd or even harmonics are governed by the parameter ϕ. For a special case of $\phi = m\pi$ with m an integer number, the main vibration frequency will be absent in the spectrum!

At the vicinity of the quadrature points where $\phi = m\pi + \pi/2$ (depicted by a dark dot in the Fig. 1), the sensitivity of the detected intensity to the displacement of the vibrating object is maximum. For an enough small vibration amplitude, the response function of the LDV system will be approximately linear. So, this technique is mostly used in the detection of the ultrasonic waves that the amplitude of vibration is generally limited to around few tens of nanometer or less [14].

In Fig. 1 a typical sinusoidal vibration of an object and its simulated HoLDV signals are plotted. According to the figure, each of two adjacent regions where the intensity variation is slow,