

TRACEABLE VIBRATION AMPLITUDE MEASUREMENT WITH A LASER INTERFEROMETER

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Received May 12, 2009

An interferometric setup to observe and measure vibration displacement using the fringe counting method is demonstrated. The uncertainty of the method is reduced by implementing the fringe phase analysis in the stationary points of the vibration cycle. Displacements of the order of micron are obtained for a full cycle vibration, with a working resolution of $\lambda/2$. Several vibration frequencies and amplitudes are used.

Key words: Interferometry, interferometers, vibration, vibration analysis, motion detection, metrology.

1. INTRODUCTION

The need for accurate measurement of vibration in a wide variety of industrial applications has brought to general attention the necessity of measurement of vibration amplitude in internationally accepted standard procedure and instrumentation. Interferometry is directly connected with the definition of meter and, consequently, is a method able to assure the traceability of displacement (or vibration) measurement [1]. Consequently, the wavelength (or in the case of interferometry, subdivisions of the wavelength) of the laser is the intrinsic measuring unit.

Depending on the frequency range, a few methods for measuring the vibrations are available, such as the Fringe Counting Method (FCM), the Minimum Point Method (MPM) and the Sine – Approximation Method (SAM). As stated in the ISO/DIS-5347-1 paper [2], these methods cover the whole frequency range from 1 Hz to 10 kHz. The FCM method can be reliably applied in the range 1–800 Hz, while the MPM is used for measurements in the range 800 Hz–10 KHz and SAM in the range 1 Hz–10 kHz.

More advanced interferometric setups are used to measure both displacement and phase of the vibrations [3–5] and even with higher resolution [6]. Others can visualize

vibration modes, measure displacement and phase of vibrations of rough surfaces, such as speckle interferometry [7, 8].

In this paper we describe a simple interferometric setup to measure vibrations using FCM. We use the fringe phase analysis in the stationary points of the vibration cycle in order to reduce the uncertainty of the measurement. Displacements of the order of microns are obtained for a full cycle vibration. We can apply this work to calibrate accelerometers [9] in the first frequency range from the three described above.

2. MEASURING SYSTEM

The measuring system is a Michelson interferometer with collimated beam, as shown in Fig. 1. A stabilized He-Ne laser @ 632.8 nm is used as light source, S, and the laser beam is expanded and collimated using a beam expander, E (composed of a lens system and a pinhole), and a short focal length lens, L.

A beam splitter cube, BS, is used to split the incident collimated laser beam and send it towards the two mirrors of the interferometer. The reference mirror, M_{ref} , is attached to a steering mirror mount for an easier adjustment of the position of the reference beam, while the measuring mirror, M_{meas} , is placed on a shaker that will make it vibrate in a controlled way. Namely, the shaker will cause the mirror to vibrate longitudinally back and forth in a sinusoidal manner. An oscilloscope is connected to the output of the photo detector, D, in order to visualize and record the signal. All these components of the measuring system are placed on a vibration isolated optical table. The driving signal for the shaker is controlled by computer software.

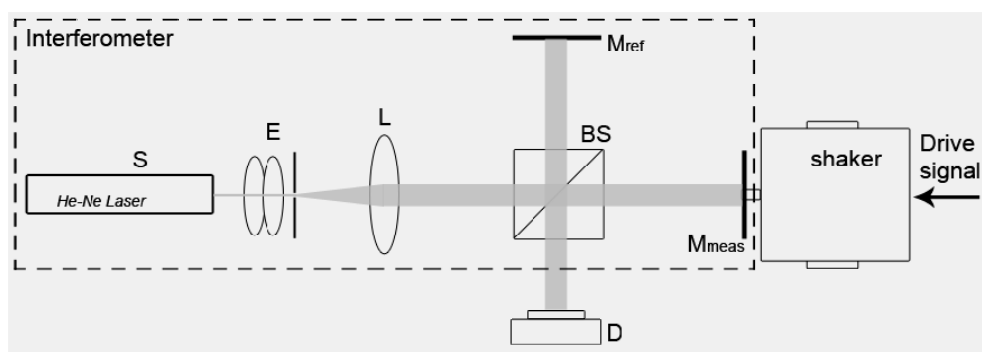


Fig. 1 – Diagram of the vibration measuring system: S – HeNe laser source, E – beam expander, L – collimating lens, BS – beam splitter, M_{ref} – reference mirror, M_{meas} – measuring mirror, D – photo detector and a shaker.

Several sinusoidal signals with various frequencies and amplitudes are produced, recorded and analyzed. We chose a random set of six frequencies and

amplitudes of vibration in the range 38–118 Hz. A theoretical description of the method is given bellow (please, see “Theoretical approaches”) and the results and conclusions are discussed under “Experiment and results”.

3. THEORETICAL APPROACHES

When the mirror M_{meas} is subjected to vibrations from the shaker, the detector output signal can be described by the equation [1, 2]:

$$V(t) = V \cos[\varphi_0 + \varphi_m \cos(\omega t + \varphi_s)], \quad (1)$$

where t is time, V denotes the voltage amplitude, φ_0 is the initial phase of the signal (depends on the initial optical path difference), ω is the angular frequency ($\omega = 2\pi f$ where f is the vibration frequency), φ_s is the vibration zero phase and φ_m is the modulation phase amplitude ($\varphi_m = 2\pi d/\lambda$, d being the amplitude of the measuring mirror M_{meas} and λ the wavelength of light).

In the present interferometer, the displacement of M_{meas} corresponding to the distance between two adjacent fringes of the same kind (e. g. intensity minima or maxima) is given by $l = \lambda/2$. Thus, the number of fringes of the same kind (integer value) moving in front of the photodetector during one vibration cycle is given by

$$N = \frac{4d}{\lambda}. \quad (2)$$

At higher frequencies, when the value of N is small, the measurement errors become significant. In order to reduce this error we apply the procedure described in [4]. According to it, the corrected value of the displacement amplitude is given by

$$d_c = \frac{\lambda}{4\pi} \left(N\pi + \frac{|V(t_{rs})|}{V(t_{rs})} \frac{V_{ps}}{V_{ps}} \cos^{-1} \left| \frac{V(t_{rs})}{V_{ps}} \right| + \frac{|V(t_{re})|}{V(t_{re})} \frac{V_{pe}}{V_{pe}} \cos^{-1} \left| \frac{V(t_{re})}{V_{pe}} \right| \right), \quad (3)$$

where $V(t_{rs})$ and $V(t_{re})$ are photodetector output signals at the start and the end stationary points of the vibration cycle (see Fig. 2). V_{ps} and V_{pe} are the peak values preceding the start and end stationary points.

Fig. 2 represents a theoretical plot of Eq. (1) showing the quantities we need to measure in order to compute the corrected displacement. The following parameters of the function in Eq. 1 were used for the plot: $V = 0.05$ V, $\varphi_0 = 0.01$ rad, $\varphi_m = 2\pi d/\lambda$ (with $d = 10^{-6}$ m and $\lambda = 632.8 \cdot 10^{-9}$ m), $\omega = 2\pi f$ (with $f = 72$ Hz) and $\varphi_s = 0.05$ rad.

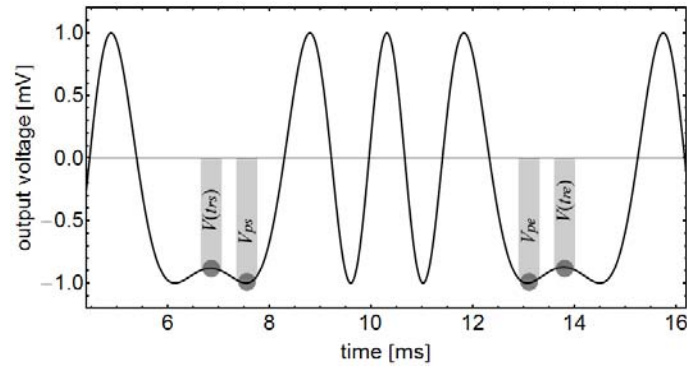


Fig. 2 – Photodetector output signal for half of the vibration cycle (or full cycle if we imagine the second part of the vibration as symmetric with the first one and propagating reversed in time). The parameters $V(t_{rs})$, $V(t_{re})$, V_{ps} and V_{pe} are also shown. The vibration frequency is 72 Hz.

With light gray bands we represented the distances from zero level (median line) to the stationary start and end points ($V(t_{rs})$ and $V(t_{re})$) of the vibration cycle together with the peak values (V_{ps} and V_{pe}) preceding the start and end stationary points. Note that Fig. 2 shows only half of the vibration cycle of M_{meas} . We may see it as the full vibration cycle if we imagine that the second part of the vibration cycle is symmetric with the first one and that it is propagating reversed in time. With dark gray dots we marked the position on the graph of the above mentioned points.

4. EXPERIMENTAL AND RESULTS

The experimental setup is shown in Fig. 3. Our experiments consisted in analyzing several vibration displacements using FCM, that is, to calibrate the shaker and the interferometer for the specific vibration frequencies. Different frequencies and amplitudes of vibration were used in the measurements.

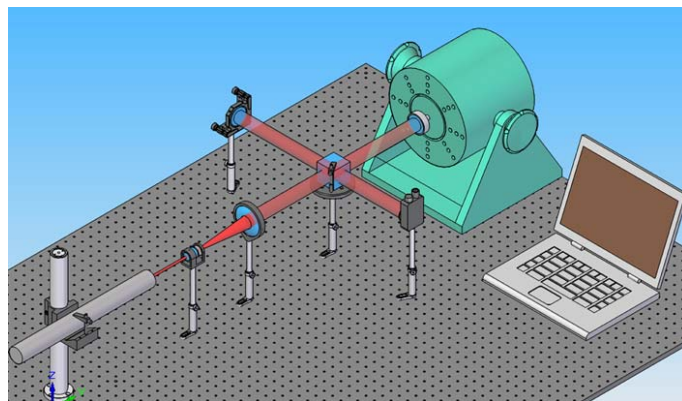


Fig. 3 – Experimental setup.

In Fig. 4 the photodetector output voltage versus time is plotted for five different frequencies and amplitudes of vibration. The frequencies are known to us because they are settings of the shaker chosen by us. We have identified from fig. 4 the values of the quantities illustrated in Fig. 2 and N for each measurement necessary for the calculations of amplitude of vibration d_c . The results are shown in Table 1.

Table 1

Values of $V(t_{rs})$, $V(t_{re})$, V_{ps} and V_{pe} and N for each frequency of vibration determined from the experimental curves of fig. 4. The values for the corrected displacements calculated using Eq. (3) are also shown

| ν [Hz] | $V(t_{rs})$ [mV] | V_{ps} [mV] | $V(t_{re})$ [mV] | V_{pe} [mV] | N | d_c [μm] |
|------------|------------------|---------------|------------------|---------------|-----|-------------------------|
| 38 | -0.85 | -0.94 | -0.97 | -0.97 | 14 | 2.3 |
| 72 | -0.06 | -0.89 | -0.51 | -0.85 | 6 | 1 |
| 82 | -0.29 | -0.81 | -0.24 | -0.71 | 26 | 4.2 |
| 87 | 0.52 | -0.8 | 0.1 | 0.71 | 10 | 1.6 |
| 115 | -0.49 | -0.83 | -0.97 | 0.97 | 12 | 2 |
| 118 | -0.38 | -0.76 | 0.8 | 0.8 | 8 | 1.4 |

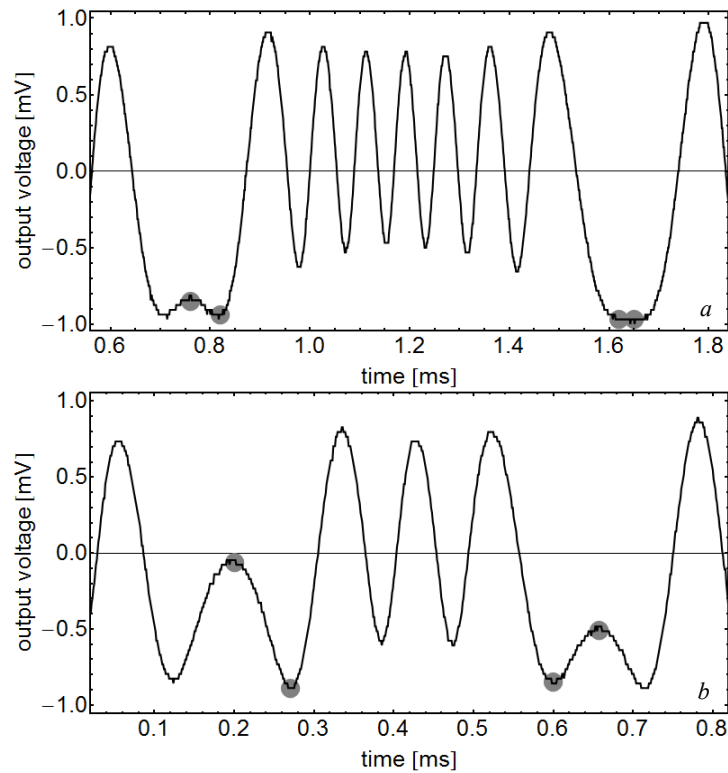


Fig. a,b

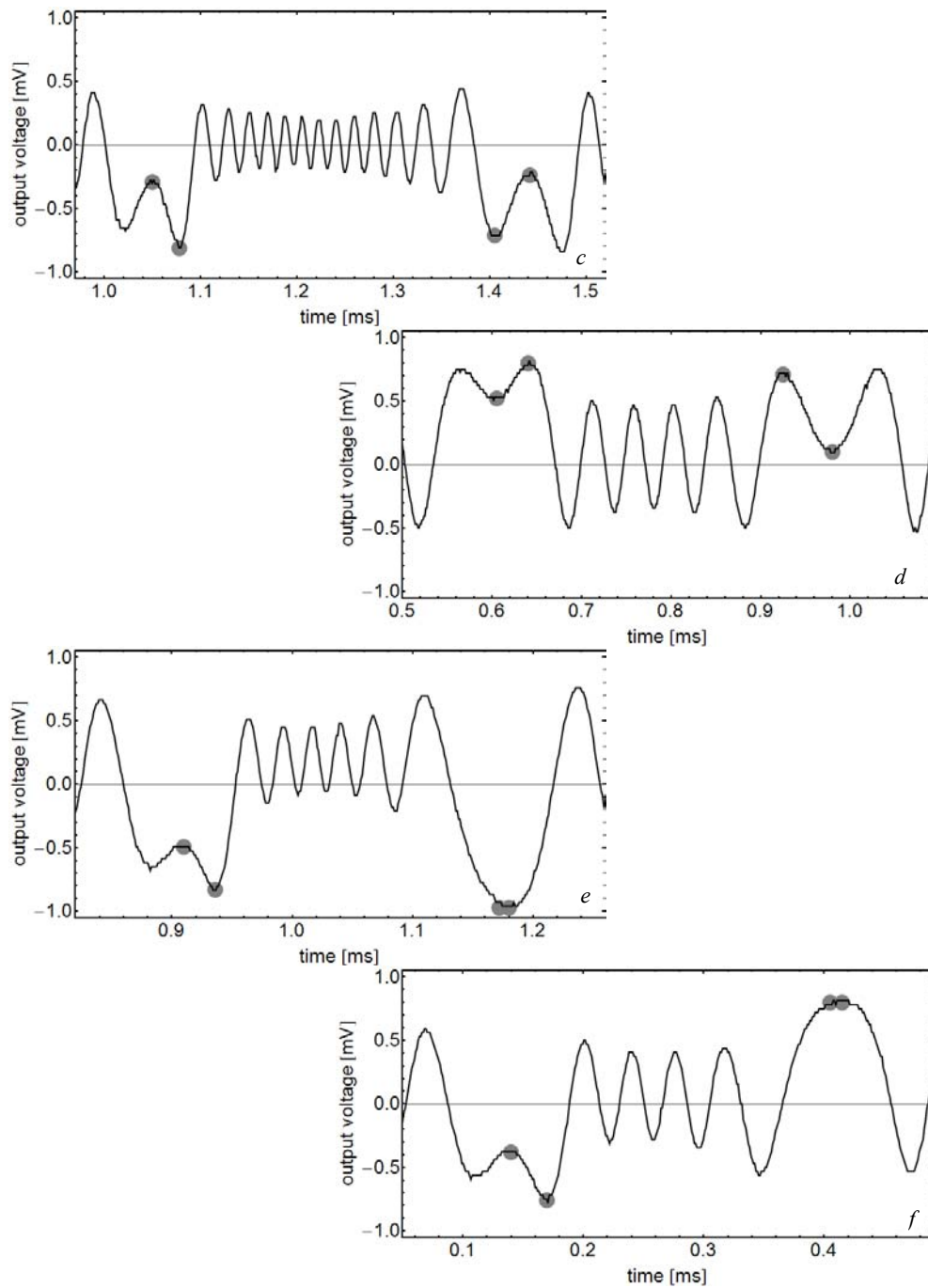


Fig. 4 – Photodetector output signals for vibration with the following frequencies: (a) 38 Hz, (b) 72 Hz, (c) 82 Hz, (d) 87 Hz, (e) 115 Hz, (f) 118 Hz.

The time plot is not necessarily starting from zero as we cut from the entire display of vibration only half a cycle which contains the characteristic “saddle-like” shaped portion that is useful for our purpose.

5. CONCLUSIONS

A traceable vibration amplitude measurement was demonstrated for calibration of vibrations purpose. A FCM technique to compute the displacements was used. It is important to note that the “saddle-like” stationary points have slightly different shapes for each vibration frequency due to experimental imperfections or background vibration noise. This fact does not affect our measurements at this level of precision, though.

With our experiment, the amplitudes of vibration of the measuring mirror, were of the order of microns, and were measured with a resolution of $\lambda/2$. Further work includes an improved quadrature interferometer able of $\lambda/8$ or even $\lambda/16$ resolution in measurement of displacement.

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