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Cite as: AIP Advances 10, 015203 (2020); https://doi.org/10.1063/1.5138997
Submitted: 20 November 2019. Accepted: 18 December 2019. Published Online: 06 January 2020

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Submitted: 20 November 2019 • Accepted: 18 December 2019 •
Published Online: 6 January 2020

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ABSTRACT
A compact measurement system for harmonic vibration based on photoelectric array is proposed. Cooperating with a planar reflective mirror, which is fixed on the measured vibrating table, the photoelectric array outputs a vibration-sensitive signal. Theoretical model and simulation are discussed for the optical sensor. A frequency-tracking algorithm is proposed to realize effective measurement of vibration amplitude and frequency. Experiments are carried out on a precision vibrating table at different vibrating frequencies and different drive voltages, and reasonable results are achieved. Finally, taking the vibration with maximum amplitude as an example, the measurement results by laser Doppler interferometer are a frequency of 10 Hz and an amplitude of 72.25 μm, the measurement results by the optical sensor are a frequency of 10 Hz and an amplitude of 72.05 μm. Theoretical and experimental results show the feasibility of this system in harmonic vibration parameter measurements.

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I. INTRODUCTION

It is very important to measure the vibration parameters of the vibrator precisely. In most industrial fields, the vibrating strength is an important factor for the machine performance, safety, and lifetime, so the vibrating amplitude can be detected by microdisplacement measurements. Ma et al. introduced a capacitance displacement sensor in the roundness measurement and deep hole diameter measurement, but the sensor is usually a cylindrical probe and is not convenient to realize the miniaturization of the measuring device. An optical fiber sensor is composed of many regular arranged optic-fiber bundles, which can be either integrated into one output or output independently. Generally, the optical fiber sensor is based on the principle of light intensity modulation. A laser emitted from a central fiber is reflected by a measured object and received by a tightly aligned optical fiber beam, so the sensor is very sensitive to the displacement and surface reflectivity. When the measured plane and the end face of the sensor are not completely parallel, the reflected light intensity is not only affected by the displacement and surface reflectivity, but also affected by the tilt angle simultaneously. So, Puangmali et al. discussed the different fiber array and algorithm to reduce the effect of reflectivity and tilt angle.

A typical example is the tip shape measurement of aero-engine turbine blades. The measured data collected from the tip of the blade affect the engine efficiency and contain abundant information on engine health status; Binghui et al. studied the output characteristics of a double-ring coaxial optical fiber sensor under the influence of tip surface roughness and inclined angle, and established a theoretical model of blade clearance measurement. To deeply expand the application of optical fiber sensors, Yang et al. used a concave mirror to enhance the performance of the bundle fiber displacement sensor, Guo et al. discussed the improvement of the measurement range of optical fiber displacement sensors based on a neural network, and Buchade et al. simulated a double-fiber angular displacement sensor. All these studies have laid a solid theoretical and practical foundation for the feasibility of photoelectric detection.

With the quick development of technology in microelectromechanical systems (MEMS), laser emitting and receiving devices have been miniaturized greatly. Higurashi et al. developed an integrated optical microdisplacement sensor consisting of a laser emitter and three photodiodes. Inokuchi et al. developed an ultramicrodisplacement sensor consisting of a laser emitting source and two-dimensional distributed monolithic integrated photodiodes.
Takeshita et al. reported an optical ultramicrodisplacement sensor fabricated using a laser emitter and eight two-dimensional integrated photodiodes, which can measure linear displacement within an accuracy of 0.856% Full Scale at 200 μm and 1.11% Full Scale at 500 μm. WeiJia et al. proposed and demonstrated a compact fiber-optic quasi-Michelson interferometer (QMI) that comprises a fiber taper containing a refractive index modification (RIM) for microdisplacement measurements. It is obvious that the integrated optical microdisplacement sensor can be used in static or low-frequency displacement measurements to realize the miniaturization.

The purpose of our work is to build a micromeasurement system to monitor the vibration parameters of a harmonic vibrating table, which is used in the military field. Usually, the vibrating table works at a given drive signal, but the actual vibrating frequency and amplitude are possibly floating up and down, and the vibrating direction is also probably inclined a tiny angle. When the vibrating table works with some excited frequency, the real-time response is necessary to detect actively and feedback to the control system, so the immediate adjustment can be done with the closed-loop system. The vibrating frequency, amplitude, and position are important parameters to evaluate the response performance. To achieve this goal, our work includes:

1. Set up an integrated optical sensor system based on a plane mirror and photoelectric array. The photoelectric array, which includes a vertical cavity surface emitting laser (VCSEL) and nine photodiodes (PDs), is integrated into a device with a size of 2 mm × 2 mm. Eight measuring photodiodes are arranged uniformly on two concentric circles around the VCSEL and the ninth photodiode (reference PD) is shaded to measure the dark noise, which will be filtered out in other eight PD signals.
2. Set up a signal processing circuit including impedance conversion, signal filtering, and amplify for the output signals of measuring photodiodes and the reference photodiode, and then the information of vibration frequency and displacement of the measured vibrator at different positions can be obtained.
3. Set up a frequency tracking algorithm to realize fast response. Fast Fourier Transform (FFT) is applied on the sum of light intensity of inner circle photodiodes to obtain the vibration frequency £f_0$. Then, the sampling frequency $f_s$ is set 10 times of the vibration frequency $f_0$, the collected output signals of photodiodes on inner circle and outer circle are utilized to calculate the displacement, and the vibration amplitude is solved by taking three maximum displacement points for quadratic function fitting.

II. MEASUREMENT PRINCIPLE

The vibration measurement system includes an integrated optical sensor and a signal processing circuit. An algorithm is developed for the vibration measurement. The optical sensor is composed of a mirror, which is fixed on the vibrating object, and a photoelectric array, which is noncontact with the vibrating table. While the object vibrates, even if a slight tilt exists, the vibrating frequency and amplitude can be figured out by the measurement system. The diagram of the measurement system is shown in Fig. 1.

A. Composition of integrated optical sensor system

The optical sensor is the key part of vibration detection. The sensor is made up of a plane mirror and a photoelectric array device, shown in Fig. 2(a). The device has a silicon base, on which a VCSEL and eight measuring photodiodes are integrated. The eight measuring photodiodes locate evenly on two concentric circles around the VCSEL, as shown in Fig. 2(b), and a photo of the device is shown in Fig. 2(c). Because photodiodes have dark current, which affects the measurement result, here, we propose using an extra photodiode, namely PDREF, which is shaded, so that it can measure the dark noise of the photoelectric device, which will be filtered out in other eight signals.

Both VCSEL and photodiodes are MEMS components at the micrometer level, so the size of the integrated device is only about 2 mm × 2 mm. To get the optimum measurement result, the static distance between the mirror and the photoelectric array is set as $d_0 = 3–6$ mm.

B. Measurement principle of integrated optical sensor

In the process of measurement, the integrated device is kept stationary, the mirror is fixed on the vibrating table, and is aligned with the integrated device. The emitted light of the VCSEL is reflected by the mirror and received by eight measuring photodiodes. Assuming the vibrating table vibrates with an amplitude of $Δd$, then the clearance between the mirror and the integrated device is $d = d_0 ± Δd$. When $Δd$ changes with the vibration, the intensity of the reflected light received by the eight measuring photodiodes will change simultaneously.

Ideally, the vibrating table vibrates in the vertical direction of the integrated device, no tilt between the mirror and integrated device exists, and the light intensity received by the inner or outer four photodiodes in the same concentric circle is equal. Actually, the vibrating table vibrates with a little deviation from the vertical direction, namely, there is a mirror tilt of $β$ and the received light intensity of the four photodiodes in the same concentric circle will be different. Possibly, some photodiodes have larger outputs whilst the others have smaller outputs. In this case, each photodiode’s output contains the information of vibration frequency, displacement, and tilt angle to different extents.

To exactly describe the influence factors including the tilt on the optical sensor, we take the virtual image of the light source VCSEL as the zero coordinate point, and set up a Cartesian coordinate system (0-xyz) to establish the theoretical model of the optical sensor, shown in Fig. 3.

In the model, the Cartesian coordinate is based on the mirror tilt angle $β$ and will vary along time. That is to say, when there
is a different $\beta$, the coordinate axis $x, y, z$ will change with it and the relationship is unaltered and still valid, then the calculation and simulation will not be affected by the tilt.

The transverse irradiance of the Gaussian beam that emerges from point $o$ is given by,

$$I(x, y, z) = \frac{2P}{\pi \omega(z)^2} \exp \left\{ -\frac{2(x^2 + y^2)}{\omega(z)^2} \right\},$$

where $P$ is the light emitting power of VCSEL and $\omega(z)$ is the beam half-width along the $z$ axis. When the beam diverges with the half-angular width $\theta$, it is expressed as

$$\omega(z) = z \tan \theta,$$

then the light intensity received on the photodiode photosensitive surface is as follows:

$$I'(x, y, z) = I(x, y, z) \cos 2\beta.$$  

In Fig. 3, assuming the mirror tilts with an angle of $\beta$ around the $x$ axis, the coordinates of the central point of the photodiode will be

$$\begin{cases} x = 0, \\ y = (1 - d \tan 2\beta) \cdot \cos 2\beta = l \cos 2\beta - d \sin 2\beta, \\ z = d + \frac{d}{\cos 2\beta} + (1 - d \tan 2\beta) \cdot \sin 2\beta = d + l \sin 2\beta + d \cos 2\beta, \end{cases}$$

where $l$ is the distance from the photodiode light-sensitive surface to VCSEL. The light intensity received at the center of the photodiode photosensitive surface is
The light-sensitive area of a single photodiode is set as $\Omega$; then, the total light intensity received by a single photodiode is

$$I_{PD} = \int_{\Omega} I' d\Omega, \quad i = 1, 2, \ldots, 8. \quad (7)$$

It is clear that the received light intensity is affected by the following parameters:

- $P$—the light emitting power of VCSEL,
- $d$—the distance from the mirror to the integrated device (photodiodes’ light-sensitive surface),
- $l$—the distance from the photodiode to VCSEL,
- $\theta$—the half-angular width of the beam diversion,
- $\beta$—the tilt of the mirror.

For a particular optical sensor structure, $l$ and $\theta$ are constants; $P$ is regarded as a constant in an ideal situation, but it always changes with the drift of the light source; $d$ is a measured clearance in relation to the vibration amplitude, and $\beta$ is a changeable angle caused by the tilt of the vibration direction. So, the goal of this optical sensor is to eliminate the influence of light source drift and vibration tilt during the vibration measurement, make sure the measured frequency and amplitude are not interfered by vibration deflection and light drift.

C. Simulation analysis

Based on the theoretical model of the optical sensor, the simulation is carried out for the output characteristics. Here, the inner PD circle has a radius of 750 nm, the outer PD circle has a radius of 1000 $\mu$m, the photodiode photosensitive region has a radius of 55 $\mu$m, and the radius of VCSEL is ignored.

Figure 4 shows the variation of light intensity with displacement and tilt in a large range. Figures 4(a) and 4(b) correspond to PD1 and PD2, respectively, and Fig. 4(c) is the sum of light intensity received by PD1 and PD2. Obviously, the two PDs change inversely, but the sum of PD1 and PD2 shows some signs of stabilization.

For an actual vibrating system, even though the tilt angle usually remains in a small value, the optical sensor is sensitive to the tiny angle. Assuming the mirror tilts a certain angle $\beta$ around the $x$ axis in Fig. 3, as the tilt angle usually is less than 0.1°, we discuss within the angle $-0.1^\circ < \beta < 0.1^\circ$.

Then, the light intensities received by PD1 and PD2 are no longer consistent, meanwhile PD3 and PD4 remain consistent. Figure 5 shows the specific curves of the received light intensity of PD1 at the tilt angles $\beta = -0.1^\circ$, $\beta = -0.05^\circ$, $\beta = 0^\circ$, $\beta = 0.05^\circ$, and $\beta = 0.1^\circ$. and Fig. 6 shows the overlapping curves of the light intensity sum of PD1 and PD2 at above five angles.

From Figs. 4–6, it can be seen as follows:

1. When the mirror surface is not parallel to the photodiode surface, at the same displacement point, the received light intensity of a single photodiode changes with the tilt angle and the maximum change appears at the peak point.

$\omega = (d + l \sin 2\beta + d \cos 2\beta) \tan \theta. \quad (6)$

The light-sensitive area of a single photodiode is set as $\Omega$; then, the total light intensity received by a single photodiode is

$$I' = \frac{2P \cos 2\beta}{\pi \omega^2} \exp \left[ -\frac{2(\cos 2\beta \sin 2\beta)^2}{\omega^2} \right], \quad (5)$$

where
Although the received light intensity of two symmetrical photodiodes is not consistent due to the tilt of the mirror, the light intensity sum is nearly independent of the tilt angle.

The sum of light intensity received by photodiodes on the same circle can effectively eliminate the inaccuracy caused by a tilt between the mirror and the photodiode surface within a tiny range of angles.

In brief, it is just averaging the intensity will even reduce the tilt effective signals. If the mirror tilts in one direction, then all PDs on the right hand side get more intensity than the left hand side, summing up the inner or outer circle will just cancel this effect. As the inner sum is usually stronger than the outer sum, either the inner sum or the total sum of inner and outer is able to be used for FFT operation to resolve the parameters of vibration. Then, Fig. 7 shows the sum of light intensities of PD1 to PD4 on the inner circle and PD5 to PD8 on the outer circle, both sums are, respectively, expressed as follows:

\[
\begin{align*}
I_{\text{sum}1} &= I_{PD1} + I_{PD2} + I_{PD3} + I_{PD4}, \\
I_{\text{sum}2} &= I_{PD5} + I_{PD6} + I_{PD7} + I_{PD8}.
\end{align*}
\]  

(8)

The ratio of the two sums is calculated to get the value of \(R_{io}\),

\[
R_{io} = \frac{I_{\text{sum}1}}{I_{\text{sum}2}}.
\]

(9)

The ratio \(R_{io}\) is unidirectional in the entire displacement range, but linear in a small displacement range with a high sensitivity. To enlarge the linear range, the sum of inner and outer photodiodes was divided by the difference of inner and outer photodiodes, and we obtained another ratio \(R_{sd}\),

\[
R_{sd} = \frac{I_{\text{sum}1} + I_{\text{sum}2}}{I_{\text{sum}1} - I_{\text{sum}2}}.
\]

(10)

Compared with the ratio \(R_{io}\), the ratio \(R_{sd}\) shows a good linearity in a large displacement range, though the sensitivity went down slightly but remained almost constant in a wider range, shown in Fig. 8, then the vibrating amplitude can be calculated from the ratio \(R_{sd}\).

**D. Signal processing circuit**

The signal processing circuit for the integrated optical sensor is shown in Fig. 9.

Here, the VCSEL device emits a Gaussian beam with the output power 0.5 mW at 3.5 mA constant current drive, the maximum continuous forward current is 6 mA, the conduction threshold current is 2 mA, and the conduction voltage drop is 1.8 V. The output photocurrent signals of the optical sensor from the nine photodiodes are
usually at the μA level, it is necessary to enlarge the weak signals to readable values.

The photocurrent output from each photodiode is first converted into a voltage signal through a trans-impedance amplifier with a gain of $10^6$. The voltage signal is filtered by a fourth-order low-pass analog filter and amplified by a voltage amplifier, and then is converted to a digital signal through an analog-to-digital converter (ADC), and finally it is allowed to enter the microprocessor ARM (STM32F407) for digital filtering, frequency analysis, and amplitude calculation. Each of the nine photodiodes corresponds to one set of signal processing circuits, respectively.

As the signals of eight measuring photodiodes (PD1-PD8) include useful information, fluctuations of VCSEL, and the dark noise, the ninth photodiode (PD_{REF}) is used to measure dark noise. Eight output signals corresponding to PD1-PD8 first subtract the output signal of PD_{REF}, respectively, to eliminate the dark noise of photodiodes, and then they are amplified and filtered. Considering the VCSEL fluctuation will affect all the eight receiving PDs, here, we assume $f$ as the fluctuation coefficient of VCSEL, then formulas (8) will be expressed as

\[
\begin{align*}
I_{\text{sum}1}' &= f(I_{PD1} - I_{REF}) + f(I_{PD2} - I_{REF}) + f(I_{PD3} - I_{REF}) + f(I_{PD4} - I_{REF}) \\
I_{\text{sum}2}' &= f(I_{PD5} - I_{REF}) + f(I_{PD6} - I_{REF}) + f(I_{PD7} - I_{REF}) + f(I_{PD8} - I_{REF})
\end{align*}
\]  

The ratio of the two sums is calculated to get the value of $R'_{io}$ and another ratio $R'_{sd}$,

\[
\begin{align*}
R'_{io} &= \frac{I_{\text{sum}1}'}{I_{\text{sum}2}'} \\
R'_{sd} &= \frac{I_{\text{sum}1}' + I_{\text{sum}2}'}{I_{\text{sum}1}' - I_{\text{sum}2}'}
\end{align*}
\]

From expression (11) to expression (13), we can find that the light intensity sum is sensitive to the fluctuation of VCSEL, with the ratio of nine PD output signals, the fluctuations of VCSEL and tilt angle of vibration direction and dark noise of PDs on measurement can be effectively eliminated simultaneously.

In this system, a 24-bit delta-sigma analog-to-digital converter ADS1278 with data rates up to 144k samples per second (SPS), allowing simultaneous sampling of eight channels, is used to sample the signals from eight measuring photodiodes and single-channel ADS1271, and also a 24bit ADC microchip is used to sample the output of the ninth photodiode. The two ADCs always work synchronously through a sync control signal to make sure that they
sample simultaneously. The sampling, calculation, and data transmission are completed within one period (100 μs for the maximum sampling frequency 10 kHz), so the measurement is in real time.

E. Algorithm of vibration parameters

The algorithm is supposed to recognize the frequency and the amplitude of a precision vibrating table from the amplified sensor signals. According to the above theoretical and simulation analysis, the light intensity sum of either inner PDs or outer PDs is independent of the tilt angle, so one of the sums is utilized to figure out the frequency through FFT, and the ratio of two sums is used to calculate the vibrating amplitude.

1. Frequency algorithm

As we have seen from Fig. 7, the sum curve has a maximum at a specific clearance value, therefore, the response can be very nonlinear depending on the clearance set-point, this may not lead to incorrect frequency determination. We need a vibrating signal in time domain for FFT, not an absolute value of sum. Indeed at some set-point, the sum is composed of a static signal and a dynamic signal, the static signal depends on the clearance set-point and the dynamic signal depends on the vibrating amplitude. Therefore, when we conduct FFT, a signal filtering is necessary to remove the DC signal. From Fig. 8, the ratio has a good linear area at some clearance, we will set the initial clearance between the mirror and the integrated device in a linear area to make sure the displacement measurement in a linear area.

When the vibrating table begins to vibrate within a given frequency $f_{\text{max}}$, the microprocessor starts sampling the four signals corresponding to PD1, PD2, PD3, and PD4 synchronously with sampling frequency $f_s = 5f_{\text{max}}$, until 2048 data points are collected from each photodiode signal. FFT operation is made for the sum of PD1 to PD4, and the vibration frequency $f_0$ corresponds to the frequency with the maximum amplitude of FFT.

2. Amplitude algorithm

After obtaining the vibration frequency $f_0$, we will start the amplitude calculation. The microprocessor resets the sampling frequency $f_s = 10f_0$ for frequency tracking to avoid the excessive sampling frequency to waste data resources. Each photodiode signal is collected 10 times in a vibration period, that is, the corresponding 10 ratios are calculated in a vibration period. Among the 10 ratios, the data point with a peak value is defined as point 1, the left is point 2, and the right is point 3. Specially, if the peak point is coincidentally the first point, the adjacent two data points after it are selected as point 2 and point 3. If the peak point is just the last point, the neighboring two data points before it are selected.

During the data collection process, to avoid getting random noise signals, we need a digital filtering, which is called denoise, afterwards these three data points are used to fit a quadratic function $y = ax^2 + bx + c$. According to the Veda theorem, the maximum value of the quadratic function is $(4ac - b^2)/4a$, which is the extreme

---

**FIG. 10.** Maximum data point and polyfit curve in amplitude calculation of the measurement system.

**FIG. 11.** The data acquisition and signal processing flowchart.
point of a vibration period, the maximum is then calibrated to the amplitude of the single-frequency sinusoidal vibration.

Figure 10 shows a schematic diagram for quadratic fitting. "Vibration curve" is the sinusoidal vibration curve, "Data point" is the peak point used to calculate the amplitude, and "Polyfit curve" is the quadratic curve fitted from the three data points.

3. Algorithm flowchart

When both frequency and amplitude are obtained in a cycle, the program will go back to start again. If the vibration table vibrates in the same frequency and amplitude, we will get the same results in the second cycle. This will repeat again and again until the vibration table changes its parameters, then the new frequency and amplitude will be measured by the system. The data acquisition and signal processing flowchart of the system controlled by microprocessor ARM is shown in Fig. 11.

III. EXPERIMENT AND RESULTS

In order to understand the performance of the optical sensor system and accuracy of the parameter algorithm, we tested under static conditions to observe the sums of inner PDs and outer PDs, and calculate the ratio of sum and difference. Then, we tested with a PI vibrating table; the frequency and amplitude were figured out with the parameter algorithm.

A. Static experiment

The static experimental setup is shown in Fig. 12. The main experimental apparatus includes an integrated optical device, a mirror, a multitooth dividing table, a laser interferometer, and a circuit holding device. An optical device with a 300 μm diameter composed of a VCSEL and nine PDs was fabricated on a silicon base of 2 mm × 2 mm (Board_1) and Board_1 was fixed on the stationary fixture. On Board_2 is the signal processing circuit, which was connected with Board_1 by pins. The mirror of 5 mm × 5 mm was fixed on its stationary fixture, facing towards the optical device. The device fixture was fixed tightly on the precise moving stage and the mirror fixture was located on the multitooth dividing table to adjust the tilt precisely between the mirror and the sensor. All fixtures and a laser interferometer were fixed on an optical table for mechanical stability. The high-precision laser interferometer was applied to subtly measure the displacement and the angle between the mirror and the integrated device.

When the laser interferometer is measuring from an orthogonal direction to the integrated device, it measures angle. When it is measuring along the direction of the integrated device movement or vibrating motion, it measures displacement.

Before experiment began, the clearance between the mirror and the integrated device was set to 1 mm as an initial displacement by adjusting the moving stage. The tilt between them was set to 0° through adjusting the rotation stage and kept 0° during the process of static experiment. Then, the integrated device was moved gradually with the increment of 250 μm; the voltage output of all photodiodes was measured correspondingly in the displacement range of 1 mm–11 mm. Meanwhile, the laser interferometer was applied to measure the exact displacement of the integrated device.

Figure 13 shows the experimental curves of the output signal sum of the inner and outer photodiodes and the ratio curve.
FIG. 13. Experimental curves under static conditions with the (a) sum of inner PDs and outer PDs and (b) ratio $R_{sd}$.

Compared with the theoretical curves in Fig. 7, it can be seen that the experimental results are basically consistent with them, but not completely the same. As we have known, the simulation was made in an ideal situation and the experiment was done under actual conditions. The optical sensor with a dead zone in the displacement area of 0–4 mm will lead the receiving signals weak, so do the receiving signals with the displacement above 10 mm, the ratio in these two areas is not accurate. In the displacement range of 4–6 mm, the ratio $R_{sd}$ shows good linearity and a good agreement with the simulation. In the meantime, both sums have good response curves in the displacement range of 4–6 mm, so the area is suitable as the working range of optical sensors with a good linearity.

Through the static experiment, the relationship between the ratio and displacement was obtained, then we can set the initial position of the vibrating table in the dynamic experiment to make sure it vibrates within the linear area of the optical sensor.

B. Dynamic experiment

The dynamic experiment was carried out by replacing stationary fixture of the mirror in Fig. 12 with the piezoelectric ceramic vibrating table (PI Linear Piezo Positioning System with size $44 \text{ mm} \times 44 \text{ mm}$ and travel range $120 \mu\text{m}$, model P-611.3, PI Company), then fixing the mirror on the vibrating table and aligning with the integrated device. As the optical sensor system measures through the mirror reflecting light to eight photodiodes, the slight tilt between the mirror and photodiodes can be eliminated with the sum of inner circle photodiodes or outer circle photodiodes, and therefore leveling between the mirror and the integrated device was not necessarily required.

The system should work no matter how the mirror is attached to the vibrator, as long as the tilting angle between the mirror and the photodiodes receiving surface is less than $0.1^\circ$, which could be due to installation or introduced from the vibration process.

Actually, the PI vibrating table was excited with different drive voltages and drive frequencies to produce desired vibration. We conducted vibration experiments on the vibrating table at 10 Hz, 40 Hz, and 80 Hz, with the drive voltage is 5 V, 10 V, 20 V, 30 V, 40 V, 50 V, 60 V, 70 V, and 80 V, respectively, and obtained reasonable results. In the dynamic experiment, a laser Doppler interferometer (OptoMET) was used to measure the vibration of the PI vibrating table to compare with the optical sensor system.

1. Test results by laser Doppler interferometer

We first measured the vibration with a laser Doppler interferometer and obtained the vibrating amplitude, which could be used for calibration of the optical sensor.

| Drive voltage (V) | Displacement at frequency 10 Hz (μm) | Displacement at frequency 40 Hz (μm) | Displacement at frequency 80 Hz (μm) |
|------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| 5                | 0                                    | 0                                    | 0                                    |
| 10               | 5.850                                | 3.580                                | 5.5900                               |
| 20               | 13.050                               | 7.1900                               | 12.300                               |
| 30               | 20.975                               | 11.400                               | 20.075                               |
| 40               | 30.250                               | 15.900                               | 28.280                               |
| 50               | 39.500                               | 21.175                               | 37.250                               |
| 60               | 49.450                               | 25.500                               | 46.5000                              |
| 70               | 59.000                               | 31.250                               | ...                                  |
| 80               | 72.500                               | 35.500                               | ...                                  |

FIG. 14. PI vibrating table output displacements at different drive voltages.
FIG. 15. Eight PD outputs at different drive voltages and frequency of 40 Hz with (a) drive voltage 20 V, (b) drive voltage 40 V, and (c) drive voltage 70 V.
Table I shows the test results by the laser Doppler interferometer; the drive voltage changes from 5 V to 80 V and the frequency is at 10 Hz, 40 Hz, and 80 Hz. Figure 14 shows the relationship between the vibrating displacements and the drive voltages at different frequencies.

2. Test results by optical sensor system

The optical sensor system was used to test the PI vibrating table at different drive signals to obtain the reliable test results. As the final product will test the vibration frequency range of 100 Hz–1 kHz, the cut-off frequency of the low-pass filter is set as 3 kHz. In this experiment, the given maximum vibration frequency $f_{\text{max}} = 80$ Hz, based on the algorithm in Fig. 11, the original sampling frequency was set as five times of 80 Hz, that is, $f_s = 5f_{\text{max}} = 400$ Hz.

We took the vibration frequency 40 Hz in Table I as an example, the output signals of eight PDs were filtered by a 100 Hz low-pass filter. Figure 15 shows the results collected in 20.5 s–21 s when the drive voltage is 20 V, 40 V, and 70 V, respectively. It is obvious that each of the eight PDs represents a different position information, the inner circle four PDs have a larger output than outer circle four PDs, and all the PD outputs increase with the drive voltage.

3. Test results of vibration frequency

According to the test results of the laser Doppler interferometer in Table I, the maximum displacement of the PI vibrating table is $72.5 \mu m$. Here, we took the drive voltage of 80 V and frequency of 10 Hz as an example, measuring the vibration parameters of the PI vibrating table with the optical sensor system. Figure 16 shows the four photodiodes’ signals collected in 20.5 s–21 s before the low-pass filter, PD1 and PD2 are in the inner circle, and PD5 and PD6 are in the outer circle.

Obviously, there are some fluctuations in the original signals. As we have analyzed above, the possible reasons are as follows: ① there is a light fluctuation in the VCSEL, ② the stray light is inevitable, and ③ there is dark noise in the measuring photodiodes. So, all the PD signals were processed through a low-pass filter and amplifier, then the sum for the inner circle and outer circle was solved, respectively, as formulas (11).

As the inner sum is much bigger than the outer sum, the sum of inner circle four PDs was chosen to conduct FFT. Figure 17 shows the outputs of four PDs in the inner circle. It shows that the fluctuations were eliminated through filtering and dark noise processing. From the processed signals, we could clearly find that the light intensities of PD1 and PD2, and PD3 and PD4 were not completely consistent during the vibration caused by obliquity in the x and y directions, because the information of vibration frequency, displacement, and tilt angle is possibly contained within each PD’s output to different extents.

Figure 18(a) shows the sum of the output signals of the four PDs, which we used to calculate the vibration frequency. As we could see, there was a DC component, which was related to the static distance $d_0$ in the sum curve, so we removed the DC component via a digital filter, leaving only the sinusoidal signal related to the

![FIG. 17. Time domain signal of the vibration table under an excitation voltage of 80 V and a frequency of 10 Hz.](image-url)
vibration displacement \( \pm \Delta d \). Figure 18(b) shows that the vibration center frequency measured by FFT was 10 Hz, which was the same as the drive frequency of 10 Hz.

4. Test results of vibration amplitude

Based on the FFT theory, the vibration amplitude can be calculated from Fig. 18(b). However, there is still a VCSEL fluctuation in the sums of formulas (11), so the ratio calculation of formula (12) or (13) was used to eliminate the light fluctuation of VCSEL. With the ratio \( R_{sd} \), the vibration amplitude could be solved precisely.

As the vibration frequency \( f_0 \) was known in this experiment, the sampling frequency was reset to 10 times the vibration frequency, that is, \( f_s = 10f_0 = 100 \) Hz. Then, 50 points were collected by the optical sensor system in 0.5 s, the calculated displacement results are shown in Fig. 19. This could avoid the excessive sampling data greatly on the basis of ensuring accuracy.

The blue dotted line is the measured vibration curve, the blue dots are the sampling points collected in 0.5 s by the optical sensor, and the yellow curve is the quadratic fitting result from three data points of wave peak. The peak value of fitted curve is used only to estimate the amplitude of one measurement. Here, the amplitude measured by the optical sensor was 72.05 \( \mu m \). From Fig. 13(b), the piezoelectric ceramic vibrating table was set in a reliable linear area, it was a closed loop stage with a steady and periodic vibration, so the peak measurement in a period was valid. According to the test results of the laser Doppler interferometer in Table I, the amplitude of the PI vibrating table was 72.25 \( \mu m \) under a drive voltage of 80 V and a frequency of 10 Hz, so the measurement accuracy was 0.28%.

IV. CONCLUSION

In this paper, an integrated optical sensor measurement system was discussed for harmonic vibration. A theoretical model of integrated optical sensor based on a plane mirror and photodetector array was built up, and simulation on the sensor was conducted. FFT and frequency tracking algorithm were utilized for solving the vibrating parameters.

With a planar mirror fixed on the measured object for reflecting light, the output of photodetector array is not affected by the surface reflectivity. With eight measuring photodiodes arranged uniformly on two concentric circles around the VCSEL, we can use light intensity sums to eliminate the effect due to a small tilt of the vibrator. With the ratio of two sums, the light intensity fluctuation of VCSEL is eliminated greatly. With a PDREF measuring the dark noise and being subtracted by other eight PDs, the device dark noise is filtered out in signals.

The static experiment was carried out for model verification and determination of static clearance of the optical sensor. The dynamic experiment was conducted on a piezoelectric ceramic vibrating table through a laser Doppler interferometer and the optical sensor system under different drive voltages and frequencies. The sensor model was convinced theoretically and experimentally. Finally, we took the vibration signal of frequency 10 Hz and amplitude 72.25 \( \mu m \) as an example, the measured vibration frequency by the optical sensor system was 10 Hz, and the amplitude was 72.05 \( \mu m \).

This entire measurement system has realized the miniaturization with compact MEMS technology. With this system, the vibrating frequency and amplitude can be tracked and measured in real time.

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