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Development of primary calibration system for high frequency range up to 10 kHz

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Abstract

In this paper, a new primary calibration system for the frequency range from 5 kHz to 10 kHz at the National Metrology Institute of Japan (NMIJ) is reported. In the high frequency range, the displacement amplitude becomes small and the effects of parasitic motion, such as drift motion and external noise, become greater with increasing frequency. Therefore, the realization of the primary calibration system becomes difficult. The new primary calibration system for the high frequency range is implemented with a newly designed laser interferometer and a new signal processing algorithm, which is named the multiple sinusoidal approximation method. The new designed laser interferometer has a twofold optical path to detect a small displacement with high accuracy, as well as a flexible alignment mechanism for the measurement position. The multiple sinusoidal approximation method can correct the effect of parasitic motion, which leads to high accuracy acceleration measurement. As a result, the new primary calibration system has realized a calibration capability within an expanded uncertainty of 0.5 %.

Keywords: acceleration, twofold optical path laser interferometer, multiple sinusoidal approximation method, drift motion.

1. Introduction

Three accelerometer calibration systems of national standards have been established at the NMIJ up to 2005 [1]. These systems are used for the very low frequency range (0.1 Hz to 2 Hz), the low frequency range (1 Hz to 200 Hz) and the middle frequency range (20 Hz to 5 kHz), respectively. These systems have calibration capabilities within the expanded uncertainty (coverage factor of k=2) of 1.0 % to 6.0 % for the very low frequency range, 0.3 % to 2.0 % for low frequency range, and 0.3 % to 1.5 % for the middle frequency range. Two systems for the low frequency range and the middle frequency range have been used for national calibration services and their uncertainties have been published in Appendix C of the CIPM-MRA as calibration and measurement capabilities (CMCs).

These calibration systems, however, cannot cover the entire range required by industry. In particular, primary calibration in the high frequency range up to 10 kHz is strongly required in the automobile industry.

In accelerometer calibration, the displacement amplitude becomes smaller with increasing frequency. For example, the acceleration amplitude of 100 m/s^2 at 5 kHz is equal to the displacement amplitude of 100 nm, whereas the acceleration amplitude of 100 m/s^2 at 10 kHz is equal to the displacement amplitude of 25 nm. The laser interferometer used in our institute can detect the dynamic displacement amplitude of 63 nm at minimum [2]. Therefore, this interferometer cannot be applied for small displacement below 63 nm at a high frequency such as 10 kHz. Consequently, a new laser interferometer with high accuracy is required. Additionally, the effects of parasitic motion, such as drift motion and external vibration noise, become greater with increasing frequency, leading to higher uncertainty. Therefore, a correction method for these effects, in order to reduce the uncertainty, is also required for the calibration at high frequency.

In this study, a new laser interferometer with a twofold optical path and a correction method for the effects of parasitic motion are developed. Finally, the primary calibration system for the frequency range from 5 kHz to 10 kHz is established as the new national standard in Japan, and the calibration capability is verified.

2. Laser interferometer with twofold optical path

A laser interferometer with a twofold optical path is frequently used for the static measurement to improve resolution. In this case, the twofold optical path is simply formed from a corner cube prism and some optics, as shown in figure 1.

However, if a heavy load mass such as a corner cube prism is mounted on an accelerometer in the primary calibration, the calibration result might be affected by the load. As a result, a vibration measurement of high accuracy cannot be achieved. Therefore another type of laser interferometer with a light load is required for this use. We developed a new laser interferometer with a twofold optical path using a light load mass such as a reflection mirror with a plane surface.

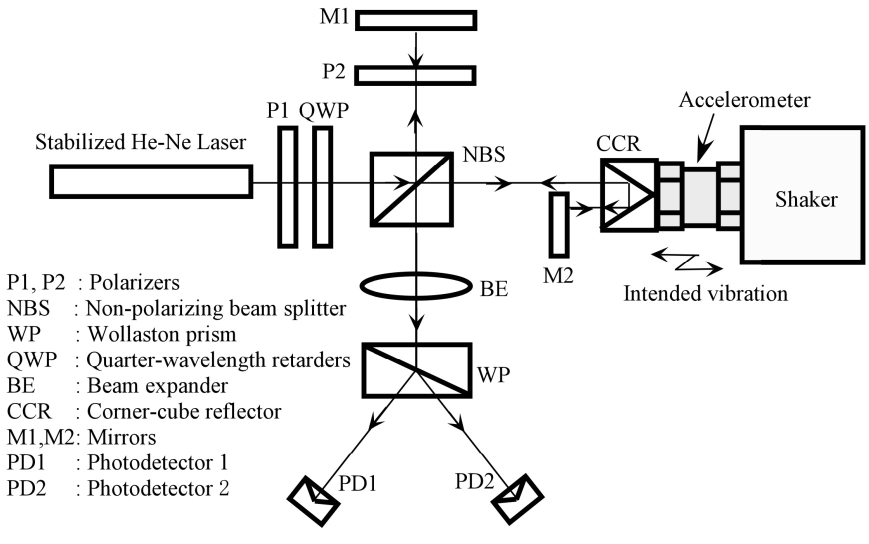

Figure 1 A conventional laser interferometer with twofold optical path

The optical setup of the newly designed laser interferometer with a twofold optical path is shown in figure 2.

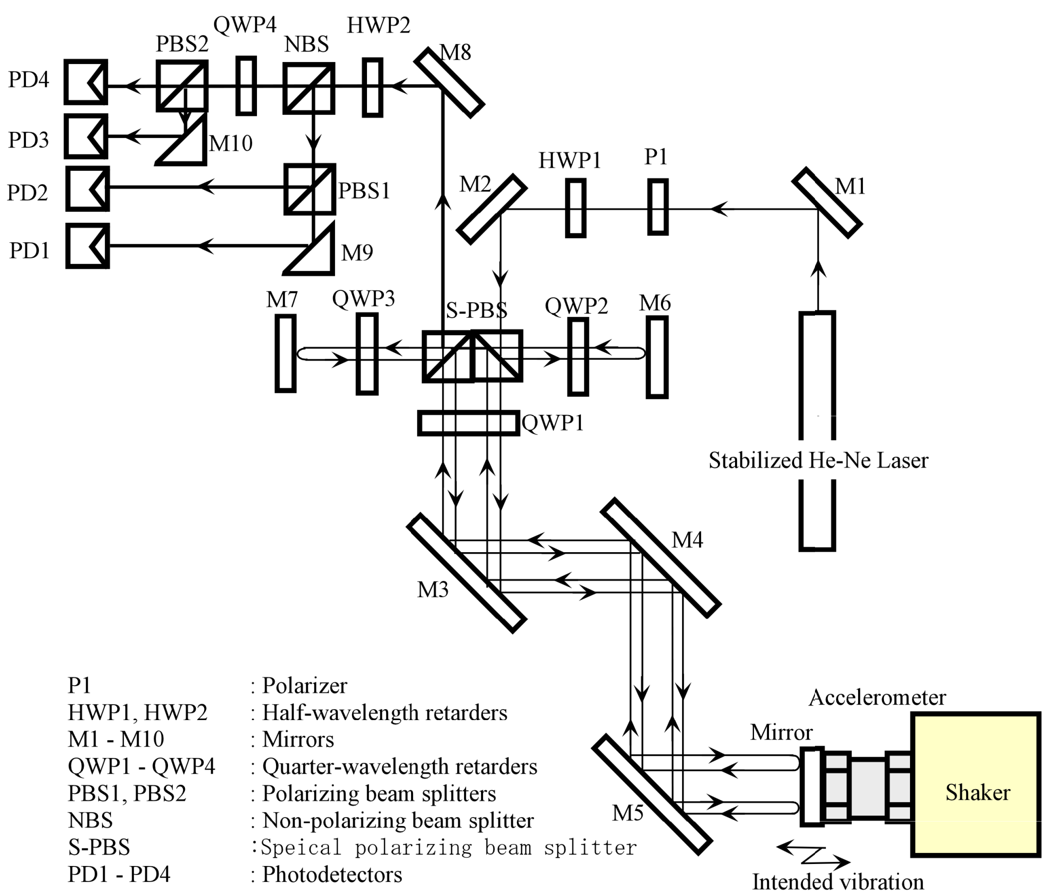

Figure 2 Optical setup for a newly designed laser interferometer

In this interferometer, the twofold optical path is built using a special polarized beam splitter attached with three triangular prisms. Figure 3 shows two patterns of the optical setup for optical paths switched using a linear stage and a rotational stage. The bold lines in figures 3 (a) and (b) show the optical paths.

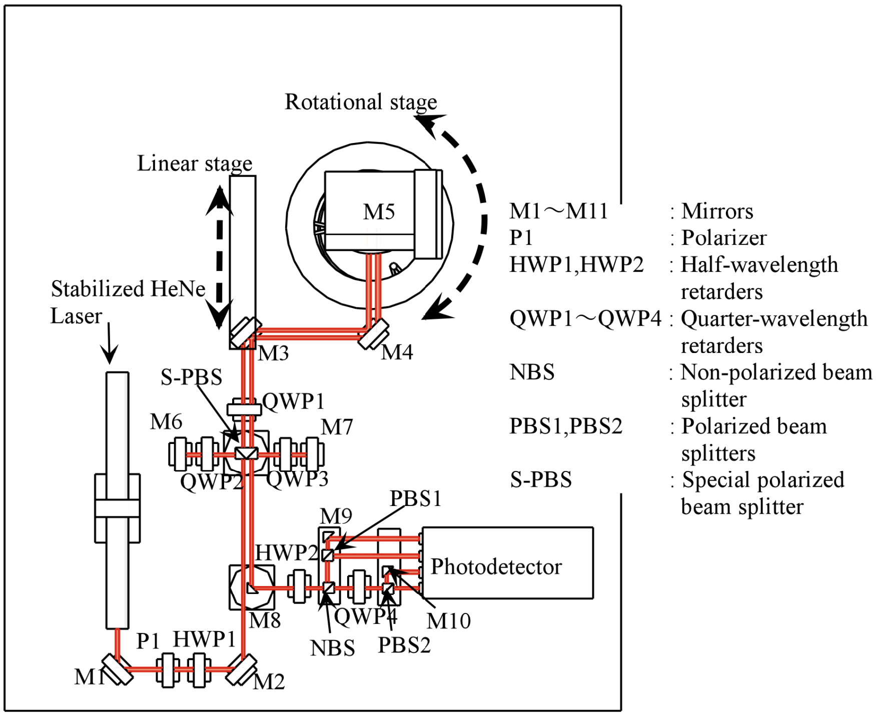

Figure 3. Optical path (a)

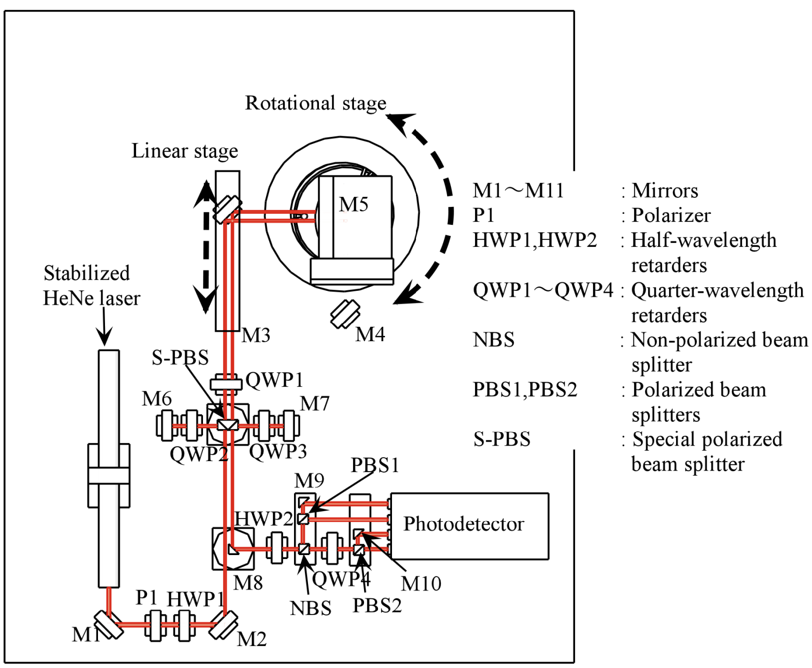

Figure 3. Optical path (b)

A stabilized HeNe laser is used as a light source. A polarized beam splitter (S-PBS) divides the laser beam into two. The measurement beam passes through a quarter-wavelength retarder plate (QWP1) and returns to S-PBS after reflection at some reflection mirrors with a plane surface (M3, M4, M5). Then, it is reflected at the slant of the S-PBS, passes through QWP1 again and returns to the S-PBS after being reflected at the same reflection mirrors (M3, M4, M5). Meanwhile, the reference beam passes through QWP2 and returns to S-PBS after reflection at reflection mirror M6. Then, it passes through S-PBS and QWP3, and returns to S-PBS again after reflection at reflection mirror M7. Finally the measurement beam and the reference beam interfere at S-PBS. The interferometry beam is divided into four beams using the half-wavelength retarder plate (HWP2), QWP4, reflection mirrors (M9, M10, M11), NBS, PBS1 and PBS2. The phase difference period of each signal is $\pi/2$. These beams are detected using four photodetectors. Two sets of detected signals, whose phase difference is π, are inputs to an differential amplifier, as shown in figure 4, leading to quadrature signals equivalent to the signal described in ISO16063-11. The differential output configuration that we adopted suppresses not only the electrical and optical noise but also the DC offset component of the signals. Thus, a high signal-to-noise ratio is expected.

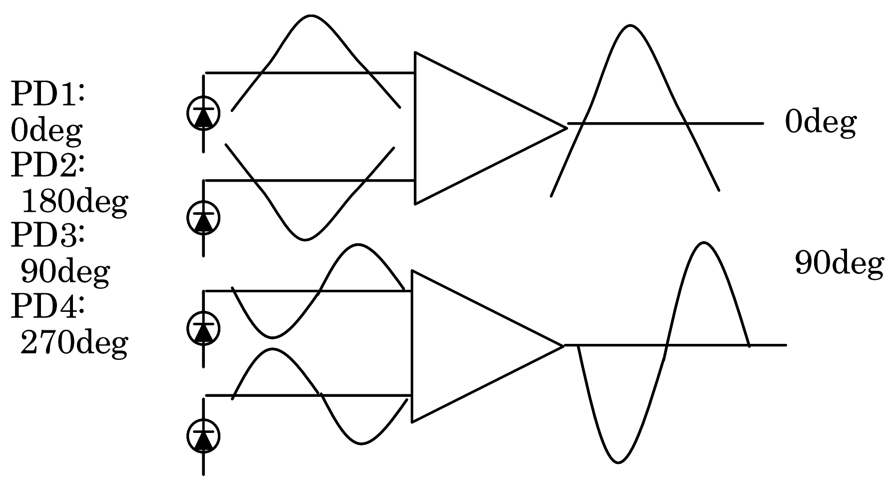

Figure 4 Photodetector output and differential operation

To enable flexible alignment of the measurement position, switching of the optical path is designed. An optical path is switched by moving M3 on the linear stage and rotating M5 on the rotational stage, as shown in figures 3 (a) and (b). Thus, many sets of different measurement points are arranged and the uncertainty contribution due to vibration distribution on the surface of the accelerometer would also be reduced.

3. Multiple sinusoidal approximation method

In the sine approximation method, which is described in ISO16063-11, the effect of parasitic motion appears as periodic noise in the residual deviation between a demodulated signal and an approximated signal. Such periodic noise induces systematic error in the approximation process.

Recently, some methods, such as filtering and wavelet analysis are applied to correct the effect of the parasitic motion [3], [4], [5], [6]. However, those methods request some special devices, such as digitizer with flexible sampling rate, or complicated processing.

In this study, a new approximation method is proposed to reduce the systematic error due to parasitic motion without any special devices or complicated processing. In the conventional sine approximation method, the demodulated signal is approximated as a pure sinusoidal waveform at the calibration frequency. Meanwhile, in our proposed method, under the assumption that the frequency of the dominant periodic noise is known beforehand, the demodulated signal is approximated as multiple sinusoidal waveforms, that comprise a sinusoidal waveform at the calibration frequency (ω) and some sinusoidal waveforms at the known frequency of dominant periodic noise (ω_j), as shown by

$$\varphi_M(t) = b_1 \cos \omega t + b_2 \sin \omega t + b_3 + \sum_{j=0}^{m-1} (c_{1j} \cos \omega_j t + c_{2j} \sin \omega_j t), \cdots\cdots\cdots \text{(1)}$$

where t is time, $\varphi_M(t)$ is the time series of the phase in the interferometry signal, m is the number of the dominant periodic noise, and b_1, b_2, b_3, c_{1j}, c_{2j} are coefficients, that are determined by least squares.

The dominant periodic noise would be generated from external motion in the vicinity of the resonance frequency of the isolation table, electric noise in the power supply of the power amplifier, and harmonic distortions of the calibration frequency. The periodic noise due to parasitic motion was experimentally evaluated and consequently, it was confirmed that the dominant periodic noise is mainly generated from external motion in the vicinity of resonance frequency of the isolation table.

Based on the results of the evaluation, a model of multiple sinusoidal approximation was determined as

$$\varphi_M(t) = b_1 \cos \omega t + b_2 \sin \omega t + b_3 + c_{11} \cos \omega_1 t + c_{21} \sin \omega_1 t, \cdots\cdots\cdots\cdots\cdots\cdots \text{(2)}$$

where ω_1 is the angular frequency of external motion in the vicinity of the resonance frequency of the isolation table.

4. Calibration capability

The calibration capability of the developed primary calibration system was evaluated. Figure 5 shows a typical calibration result. At any frequency, the expanded uncertainty is below 0.5 %. In this figure, a typical calibration result of the conventional primary standard up to 5 kHz is also shown to verify the consistency. At 5 kHz, which is only the overlap frequency, the calibration result of the developed system is in good agreement with that of the conventional system within the range of expanded uncertainty (coverage factor of k=2). Additionally, the sensitivity curves connect smoothly with each other.

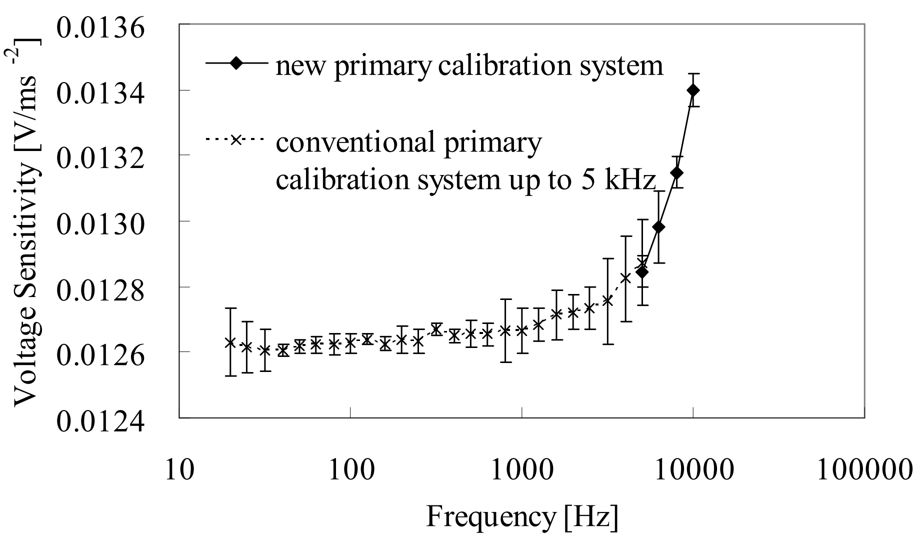

Figure 5 Typical calibration results up to 10 kHz

Table 1 shows the uncertainty budget for a typical frequency series of 6.3 kHz and 10 kHz. We should note that the experimental standard deviation of sensitivity at 6.3 kHz becomes larger. Any systematic effect, which cannot be removed by the multiple sinusoidal approximation method, would be reflected in the experimental standard deviation of sensitivity. Such an effect would be sufficiently reduced to be negligible by performing a large number of measurements.

Table 1

Typical uncertainty budget for voltage sensitivity

Frequency [Hz]		6300	10000
Acceleration amplitude [m/s^2]		100	200
Source of uncertainty			
u_1	Effect of laser wavelength stability [%]	4×10^{-7}	
u_2	Residual interferometric effects on phase amplitude measurement [%]	0.013	
u_3	Effect of interferometer quadrature output signal disturbance on phase amplitude measurement [%]	0.0047	0.0091
u_4	Effect of vibration frequency measurement [%]	0.0042	
u_5	Uncertainty of RMS voltmeter calibration [%]	0.03	
u_6	Quantization effect of RMS voltmeter [%]	2.89×10^{-5}	1.44×10^{-5}
u_7	Residual effect of output voltage measurement [%]	0.179	
u_8	Experimental standard deviation of voltage sensitivity for 8 samples [%]	0.149	0.025
Relative combined uncertainty [%]		0.235	0.184
Relative expanded uncertainty [%]		0.470	0.368

5. Conclusion

The novel primary calibration system was developed using a newly designed laser interferometer with a twofold optical path and a multiple sinusoidal approximation method to compensate the effect of periodic noise. To validate the calibration capacity of this system, the calibration was carried out. The experimental results were consistent with those of the conventional system. Calibration with a relative expanded uncertainty below 0.5 % is achieved in the high frequency range up to 10 kHz.

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