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Improved phase-detection method using an air-coupled ultrasonic wave for a few-tens of nanometers displacement measurements

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Abstract: To enhance the phase sensitivity of ultrasonic signals, phases of the multi-reference-wave are arranged around the maximum phase-sensitive region. The resolution of the phase detection is improved by magnifying the maximum sensitive phase detection outputs. A resolution of 40 nm displacement (λ/200,000) using 40 kHz air-coupled ultrasonic waves has been achieved.

Keywords: air-coupled ultrasonic wave, maximum phase-sensitivity, multi-reference-wave, phase-detection, nanometer order, displacement measurement

Classification: Science and engineering for electronics

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1 Introduction

Recently, measurements for mechanical nanometer order displacements have become increasingly essential for precision machinery and many other fields. One simple approach is to use air-coupled ultrasonic methods. The resolution of displacement measurements, however, is limited by the ultrasonic wavelength λ in the pulse-echo or time-of-flight method [1]. A higher-frequency measurement for improving the resolution cannot be achieved because of the huge attenuation of ultrasonic waves in air. High acoustic-impedance mismatching between air and ultrasonic transducers is another source of difficulty. Thus, only low-frequency measurements, around several tens of kHz can be made in air. In these situations, one possible approach for obtaining a resolution smaller than the ultrasonic wavelength λ is the phase detection technique [2]. However, few studies of the method of measuring nanometer order displacements have been reported [3]. We have only recently developed an air-coupled ultrasonic system for displacement measurements by introducing the phases of the multi-reference-wave [4]. In this system, high-accuracy phase-detection can be obtained, and a resolution of $1\,\mu$m using a 40 kHz ultrasonic wave, has been realized. One of the limiting factors for this resolution is the voltage resolution. Thus, an improved phase-detection method is required to overcome this limitation. In this paper, a novel phase-detection method, by which the phases of the multi-reference-wave are intentionally set around the maximum phase-sensitive region, will be described. To evaluate our method, experiments nanometer order displacement measurements using air-coupled ultrasonic waves of 40 kHz, will also be demonstrated.

2 Principle

When the transmitting wave signal propagates a distance z, the received wave signal has phase information $\phi(z)$. Reference waves with respect to the transmitted wave signal are used for phase detection of $\phi(z)$. In our previous paper, shifted phases δ_i $(i = 0, 1, \ldots, N-1)$ of the multi-reference-wave are introduced to accurately detect the phase information of $\phi(z)$ [4, 5]. The phase detection outputs P_i can be expressed as

$$P_i = A\cos(\delta_i - \phi(z)) = a_1 \cos\delta_i + a_2 \sin\delta_i, \tag{1}$$

where A is the amplitude of the phase detection outputs. The phase $\phi(z)$ can be expressed using $a_1 = A\cos\phi(z)$ and $a_2 = A\sin\phi(z)$ as,

$$\phi(z) = \tan^{-1}(a_2/a_1) + n\pi \quad (n = 0, 1, 2, \cdots). \tag{2}$$

Here, E is defined as the sum of the squared differences between P_i and measured values of P_i. Using the least squares method, a_1 and a_2 are determined as follows, such that E is minimized by tuning a_1 and a_2.

$$\partial E/\partial a_1 = 0, \quad \partial E/\partial a_2 = 0. \tag{3}$$

The phase $\phi(z)$ can be obtained by substituting the least squares solutions a_1 and a_2 calculated from eq. (3) into eq. (2) after measuring the phase detection

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outputs P_i at each step of the phases δ_i. When the ultrasonic propagation distance varies from z to $z + \Delta z$, the displacement Δz is finally expressed using the phase difference $\Delta\phi = \phi(z + \Delta z) - \phi(z)$,

$$\Delta z = (\lambda/2\pi) \times \Delta\phi. \qquad (4)$$

In our previous method [5], the phases δ_i are shifted by steps of $\pi/2$, namely, 0, $\pi/2$, π and $3\pi/2$. This method is the well-known four-step type of phase-shifting (FPS) method. When the slight phase variation $\Delta\phi$ is detected in the FPS method, the phase sensitivity $\Delta P_0/\Delta\phi$ for $\delta_0 = 0$ is approximately zero, as shown in Fig. 1 (a). Moreover, the variation ΔP_1 of the phase detection output P_1 for $\delta_1 = \pi/2$ is very small, even if the phase sensitivity $\Delta P_1/\Delta\phi$ is a maximum. The situations for P_0 and P_1 are the same as those for P_2 and P_3, respectively. When ΔP_1 is smaller than the voltage resolution ΔV for measuring ΔP_1, the resolution of the phase detection is limited by ΔV. To overcome this limit, the phases δ_i of the multi-reference-wave are intentionally set around the maximum phase-sensitive region, which exists at the point $\delta_1 = \pi/2$, as shown in Fig. 1 (b). The maximum phase-sensitivity is always obtained for the multi-phase detection point at each step of δ_i. The variation ΔP_i of the phase detection outputs P_i in the maximum sensitive region can be magnified larger than ΔV, so that the resolution of the phase detection can be improved. This method is hereafter referred to as maximum sensitive region multi-point phase-detection (MSMPD).

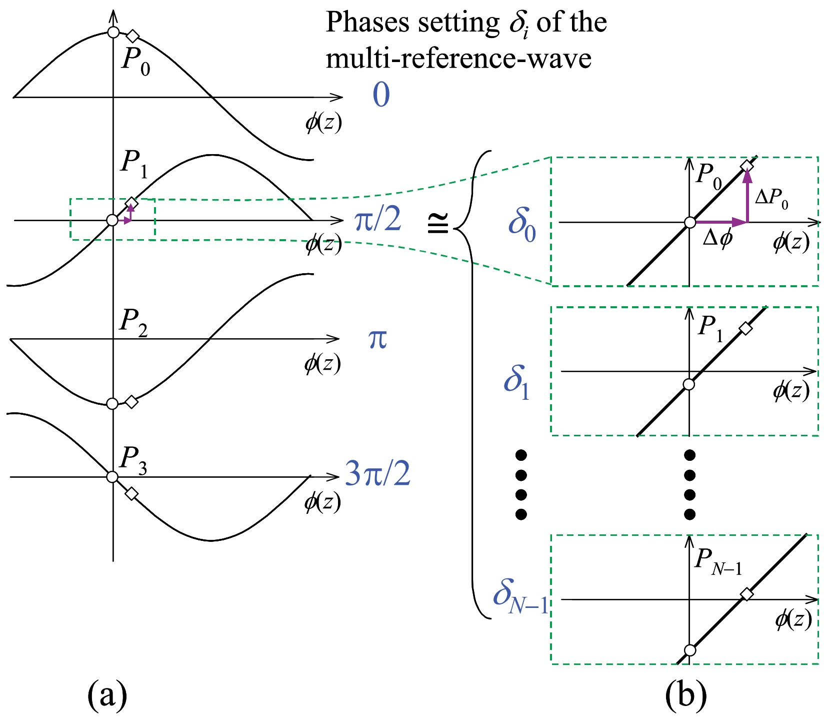

Fig. 1. A method of phases setting of the multi-reference-wave.
(a) Four-step type of phase-shifting (FPS) method,
(b) MSMPD method.

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3 Experiments

To evaluate the MSMPD method, our previous system [4] was modified as shown in Fig. 2. The transmitting transducer was driven by a continuous sinusoidal wave using the transmitting wave generator (Agilent Technologies, 33250A). The ultrasonic wave was transmitted and received in the transmission mode in air using a piezoceramic transducer (NIPPON CERAMIC, T/R40-16) having a resonance frequency of 40 kHz ($\lambda = 8.5$ mm at 20°C). The displacement Δz was set using a high-precision mechanical stage (SIGMA KOKI, SGSP80-20ZF) with an accuracy of ±10 nm. To obtain the output signals P_i, the received signal was mixed with the reference waves generated from the reference wave generator (Hewlett-Packard, HP33120A) and then fed to a low-pass filter (LPF). The phases δ_i of the multi-reference-wave were set at 0.1 deg intervals around the point of 90 deg with a resolution of 10^{-3} deg. We chose the number N of δ_i to be four for the comparison with the FPS method. A digital oscilloscope having a voltage resolution, ΔV, of 12 bits was used to measure the output signals P_i. In order to magnify the output signals P_i, the voltage range of the digital oscilloscope (Agilent Technologies, 54845A) and the voltage gain of the amplifier 1 were aligned. As a result, ΔP_i for the nanometer order displacement Δz can be larger than the ΔV of 12 bits. Figure 3 (a) and (b) show the experimental results for 0.1 μm step displacements using the high-precision mechanical stage. In the figures, the closed circles represent the average measurements of twenty trials and the error bars represent the standard deviations (SD), respectively. The SDs for the FPS method are about 0.4 μm, which is due to the 12 bit voltage resolution ΔV in the system. The SDs for the MSMPD method are significantly decreased in comparison with those of the FPS method; the resolution of the phase detection for the MSMPD method can be improved to better than ten times the FPS method. Figure 3 (c) and (d) show the experimental results from 40 and 30 nm step displacements for evaluating the resolution of the displacement using the MSMPD method. A resolution of 40 nm (λ/200,000) was successfully achieved. One of the most significant uncertainty factors in our system is the electrical noise, which is estimated to be 40 nm. When ΔP_i are magnified for the MSMPD method, the elec-

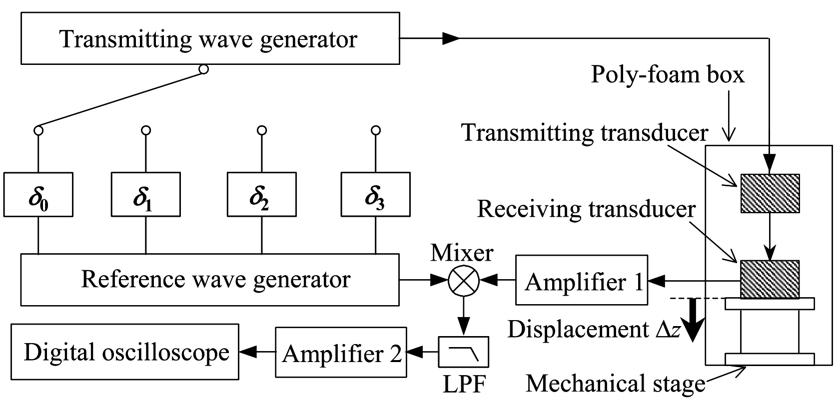

Fig. 2. Experimental set up.

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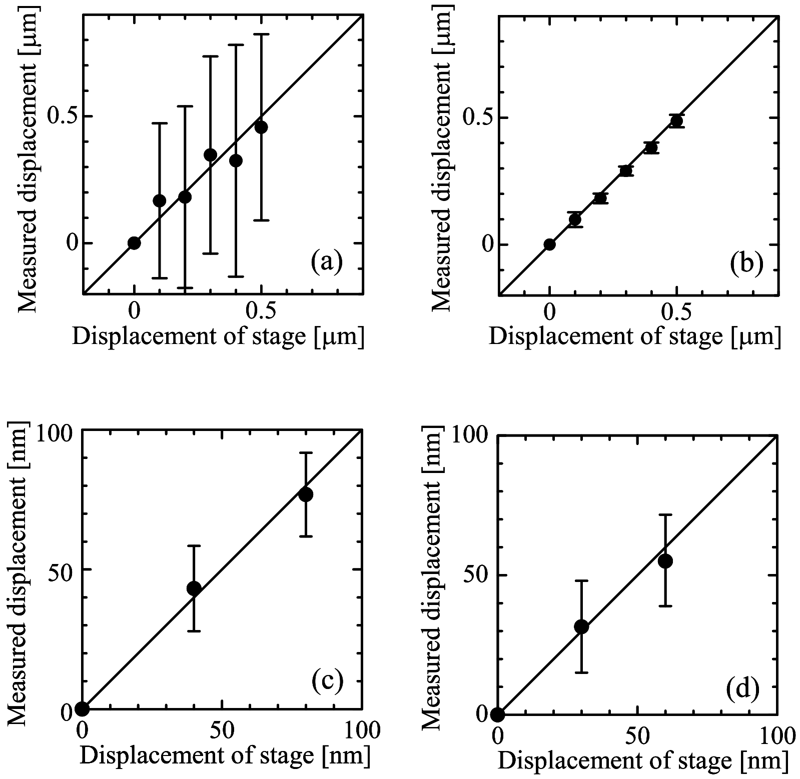

Fig. 3. Experimental results for evaluating the MSMPD method.
(a) FPS method, (b) MSMPD method,
(c) MSMPD method for 40 nm step displacement,
(d) MSMPD method for 30 nm step displacement.

trical noise will also be magnified, thus, ΔP_i smaller than this noise cannot be detected. Another uncertainty factor is the ultrasonic velocity variations caused by temperature fluctuations in the air. Temperature fluctuations of about 10^{-3}°C correspond to measurement errors of 40 nm, so that temperature control or precise monitoring should be an important feature of our future systems.

4 Conclusion

By arranging the phases of the multi-reference-wave around the maximum phase-sensitive region, the resolution of the phase detection was vastly improved. A resolution of 40 nm (λ/200,000) displacement for a 40 kHz ultrasonic wave in air, has been achieved by the MSMPD method. To obtain higher-resolution, improvement of the signal-to-noise ratio in the system is required.

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