Applications of a Pinhole-Based Low-Frequency Air-Coupled Ultrasonic System into Precision Displacement Measurements

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1. Introduction

The use of air-coupled ultrasonic waves allows noncontact measurement. Thus, an air-coupled ultrasonic system would be valid in situations where coupling fluids are not desirable, and it can also be expected to enable work in new areas\(^2-4\). An air-coupled ultrasonic wave, however, has not generally been applied to precision measurements in MHz range because a frequency range of most common air-coupled ultrasonic waves is limited to several tens of kHz. If high spatial resolution much smaller than the ultrasonic wavelength \(\lambda\) could be realized using low-frequency air-coupled ultrasonic waves, a new technique of ultrasonic precision measurements would be created.

We have previously reported the development of a pinhole-based low-frequency air-coupled 40 kHz ultrasonic system\(^1\). This system has achieved lateral \(^1, 2\) and distance \(^3\) resolutions much smaller than \(\lambda\). This report describes applications of our system into noncontact precision measurements around sub-nanometer order displacements.

2. System and its characteristic

Figure 1(a) shows a pinhole-based low-frequency air-coupled 40 kHz ultrasonic system. This system has two unique ideas. One is a conical acoustic probe (CAP)\(^1, 2\) with a pinhole to obtain a lateral resolution much smaller than \(\lambda\), as shown in Fig. 1(b) and (c). The aim of the CAP is to obtain a lateral width approximately equal to the pinhole diameter \(2a\) much smaller than \(\lambda\) near the pinhole. The conical baffle is made from a thin copper plate, and has an aperture diameter \(d\) and a tip angle \(\theta\) of 20 mm and 20°, respectively. A \(\lambda/45\) (200 \(\mu\)m) diameter pinhole was manufactured in the tip of the CAP. Using the sound field near the pinhole, a lateral resolution of \(\lambda/30\) beyond the diffraction limit, which is approximately equal to the pinhole diameter, was achieved in our previous paper\(^1, 2\). The other idea is a phase detection technique for continuous ultrasonic wave (CW) to obtain a distance resolution much smaller than \(\lambda\)\(^3\). This idea allows a narrower bandwidth of a filter in the phase detection, which accordingly improves the signal-to-noise ratio. This is one of advantages of this CW system over often-adopted pulse-echo ones\(^4\) operating in a wide-band mode. When a continuous sinusoidal wave from a function generator (Agilent Technologies, 33250A) was applied to commercially available and low-cost transducers (NIPPON CERAMIC, R40-16), the ultrasonic wave was transmitted into the conical cavity in the CAP. The transmitting wave interfered with the wave reflected from the object, and the interfered wave signals were then inputted to a phase detector (vector signal...
analyzer, Agilent Technologies, 89410A). The phase was detected for the 10-Hz filter bandwidth, and phase data was recorded on a personal computer via a general purpose interface bus (GPIB) interface.

The phase-distance ($z$) property of our system was obtained by the experiment in which phase variation was measured with increasing pinhole-object (metal block) separation (axial distance $z$). Figure 2 shows the experimental result of the phase variations against $z$ up to a pinhole radius $r=100 \, \mu m$. For a short $z$ distance, the phase was found to be highly sensitive to a slight change of $z$. The phase sensitivity around the region indicated in Fig. 2 has a maximum and an approximately linear response against a working distance of smaller than 7 $\mu m$. Applications using this region into precision measurements can be expected.

3. Applications

First application of our system is nanometer order displacement measurements in real time. The distance $z$ was sequentially changed in 50 nm steps at 2 s intervals. The phase variations measured were fed to a personal computer and then measured displacement was calculated using the measured phase and phase sensitivity which was estimated to be approximately 0.074 mdeg./nm in Fig. 2. Figure 3 shows the experimental result. In Fig. 3, the standard deviations in the flat region after transient vibrations are smaller than 5 nm. Thus, a distance resolution better than $\lambda/900,000$ (10 nm) can be achieved. One of the most significant uncertainty factors in our system is the electrical noise that is approximately 0.1 mdeg. in phase and 1 nm in displacement.

Second application is noncontact surface topographical profiling of a micrometer order height. To extend the working distance of our system while maintaining its high-resolution, an automatic distance control system was newly introduced in our system. The object of approximately 16-$\mu m$ heights in the metal block under the pinhole was scanned with automatic distance control to maintain constant maximum phase sensitivity. The controlled distance and the measured phase were reconstructed to height data. Figure 4 shows the experimental result. Height of 16 $\mu m$ is successfully measured.

4. Conclusions

Real-time displacement measurements with a distance resolution of $\lambda/900,000$ (10 nm) were demonstrated using our system. Noncontact surface topographical profiling of 16-$\mu m$ heights was also accomplished with the automatic distance control system. Future studies will involve more discussion of applications of our system.

References