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Microscopic Vibration Measurement with Thermophone and Phase Tracking Method in Air and its Application for Non-Contact Heartbeat Monitoring

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1. Introduction

Non-contact heartbeat monitoring is expected to be used for medical applications or driver monitoring system in vehicles. Heartbeat pulsation can be detected by measuring body surface vibration. There are several systems proposed for non-contact measurement, including millimeter wave, optical image, and ultrasound. In particular, ultrasound has advantages such as inexpensive, non-invasive and easy to process signals. Usually, this ultrasonic approach is based on pulse-echo and the TOF principle, where body surface displacement is measured by traveling time of reflected ultrasonic pulse.

With applying chirp ultrasound signal and using cross-correlation technique, distance resolution is improved to mm-level [1]. Nevertheless, the resolution was not to meet heartbeat detection since it appears as μm-level displacement at body surface. Therefore, higher resolution is required.

In this work, we constructed airborne microscopic vibration measurement system with thermophone. Then, displacement accuracy and performance of the system are evaluated *in vitro* with a dedicated apparatus. We also showed the performance of the system *in vivo* on clothed human body and at the top of the head.

2. Phase-tracking method

The driving signal applied to the thermophone is correlated with the received echo signal, then pulse compressed waveform is obtained. TOF is located as the time index of the peak of the correlation envelope. Multiplying TOF by speed of sound (SOS), distance is determined. In practice, each signal is digitally sampled and stored as discrete data train, then their cross correlation and its envelope are also performed digitally and discretely. Suppose SOS is 340 m/s and sampling frequency is 500 kHz, the resolution of the peak tracing will be limited to 340 μm. This displacement resolution is insufficient to detect heartbeat at body surface. However, by tracing phase value of correlation wave at the time index of the envelope peak, displacement smaller than the value limited by sampling can be determined. It should be noted that equivalent frequency f_c of the analytic signal must be determined with regarding difference from phase value adjoining time index $\delta\phi$, in order to convert phase value into displacement.

$$f_c = \delta\phi/2\pi\delta t \qquad (1)$$

where δt is the sampling period.

Even if the method can detect μm-level displacement, air movement such as wind or convection cause TOF error. It is known that these turbulences confined to low frequencies. Therefore, in order to eliminate the turbulence, we have adopted the phase-tracking method [2]. The method is based on differencing repeated pulse-echo frames. Displacement between the frames ξ is represented as,

$$\xi = (\phi_n - \phi_{n-1})/4\pi f_c \qquad (2)$$

where ϕ_n is the phase of the envelope peak of n-th frame and c is the SOS.

3. Experiments and result

3.1 *in vitro* heartbeat monitoring

Fig. 1 shows experiment diagram for distance measurement. Linear down chirp ultrasound signal (duration 10 ms) is emitted from the thermophone, then the ultrasound is reflected from the circular plate. Reflected signal is received by MEMS microphone located near the thermophone. Repetition of the chirp ultrasound signal is set up to 60 times per second (frame per second; fps), then difference (displacement) from the immediately preceding frame is calculated for each ping. The acrylic circular plate is connected to a voice coil and driven μm-level vibration by the voice coil. As reference, a laser displacement meter is used to monitor the vibration simultaneously.

Fig. 2 shows repeated accuracy of the distance measurement, where the circular plate is fixed. For low repetition, especially below 10 fps, the accuracy become sharply worse. When frame rate is 60 fps, the accuracy is less than 20 μm.

Fig. 3 shows measurement results of the plate vibrated by 5 Hz continuous sine wave. Fig. 3(b) shows temporal waveform obtained by the

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thermophone. Compared to the reference waveform in Fig. 3(a), it is confirmed that μm-level vibration is clearly measured even with airborne ultrasound.

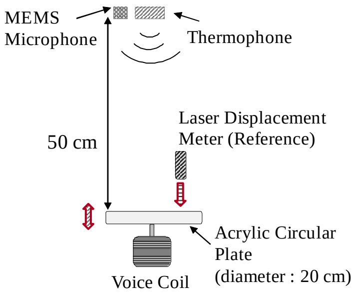


Fig. 1 Experiment diagram for distance measurement.

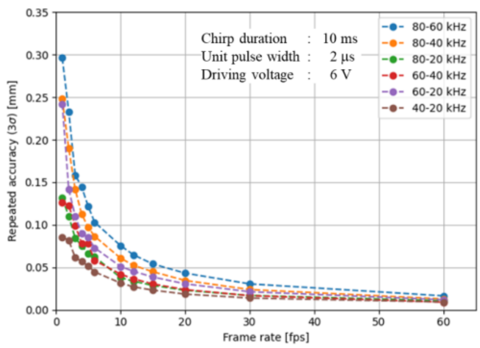
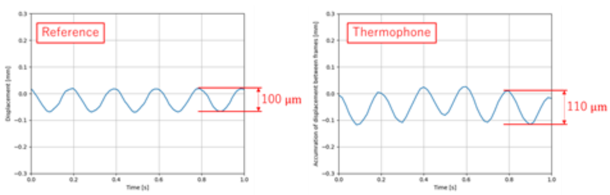


Fig. 2 Repeated accuracy of distance measurement for various chirp frequencies and frame rates.



(a) (b)

Fig. 3 Temporal waveforms of 5 Hz sine wave vibration. (a) Obtained by laser displace meter as reference, (b) Obtained by the thermophone.

3.2 *in vivo* heartbeat monitoring

Actual heartbeat is monitored by utilizing the presented system. As shown in **Fig. 4**, ultrasound is emitted toward clothed human chest or the top of the head. Examinee wears underwear, shirt and polyester jacket. The chirp band ranges from 80 kHz to 20 kHz, and pulse duration and frame rate is 5 ms and 60 fps, respectively. Electrocardiogram (ECG) is attached to the examinee for validation reference. **Fig. 5** shows displacement signals simultaneously acquired with the ultrasonic and ECG. Note that the monitoring at the chest and at the top of the head were not simultaneously. Displacement between adjacent frames is converted to velocity with multiplying frame rate, is shown in bottom of Fig. 5.

In velocity waveform, spike shape train synchronized with heartbeat pulsation is confirmed at the chest (Fig. 5(a)). On the other hand, at the top of the head (Fig. 5(b)), spike shape train synchronized with heartbeat pulsation with a 0.2 s delay is confirmed. In either case, the presented system shows availability for non-contact heartbeat monitoring in air.

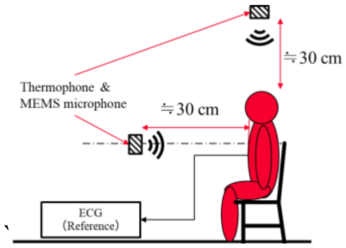
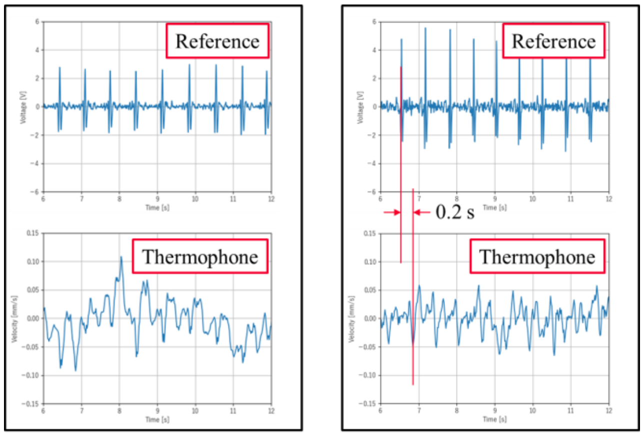


Fig. 4 Measurement layout for *in vivo* heartbeat monitoring.



(a) at the chest (b) at the top of the head

Fig. 5 *In vivo* heartbeat monitoring on human body.

4. Conclusion

In this paper, we propose a non-contact measurement of μm-level vibration designed for heartbeat monitoring. And, practical measurement system was constructed, and showed availability for non-contact *in vivo* heartbeat monitoring.

References

1. Shoya Nakade, et al., 2019 IEEE International Ultrasonic Symposium, MoPoS-30.3, (2019).
2. Hiroshi Kanai, et al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 43, pp. 791–810, (1996).