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Measurement of human body surface displacement by breathing using airborne ultrasound

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***Abstract*—We have studied about non-contact measurement of human body surface displacement by breathing using the ultrasonic pulse-echo method. The displacement by breathing can be determined by continuously measurement of the distance to the human body surface. In the case of a standing human, however, there are the displacement by body movement in addition to that by breathing. Furthermore, displacements by breathing and body movement are equal to or smaller than the wavelength of airborne ultrasound. Therefore, measurement of the displacement by only breathing using airborne ultrasound is typically difficult. We have proposed a measurement method of the displacement by breathing of a standing human. First, the SNR of the echo reflected from the body surface is improved by M-sequence pulse compression in the proposed method. Then, displacements of the front and back of the human body are estimated by tracking phase differences of echo signals. After that, displacement by body movement is canceled by difference between the front and back displacements. In this paper, the displacement by breathing of the standing volunteer was measured by the proposed method. When the volunteer is breathing, the displacement by breathing whose frequency was approximately 0.13 Hz could be measured.**

I. Introduction

There is a growing need for remote monitoring of vital information. We have studied about non-contact measurement of human body surface displacement by breathing using the ultrasonic pulse-echo method. The pulse-echo method is one of the typical methods of ultrasonic distance measurement [1], [2]. In this method, the distance to the object is estimated from the time of flight (TOF) of the echo reflected from the object. The displacement by breathing can be determined by continuously measurement of the distance to the human body surface. In the case of a standing human, however, there are the displacement by body movement in addition to that by breathing. Furthermore, displacements by breathing and body movement are equal to or smaller than the wavelength of airborne ultrasound. Therefore, measurement of the displacement by only breathing using airborne ultrasound is typically difficult.

We have proposed a measurement method of the displacement by breathing of a standing human. First, pulse compression [3], [4] is employed to the pulse-echo method for improvement of the signal-to-noise ratio (SNR) of the echo. Ultrasound with a sharp autocorrelation characteristic, which is a signal modulated by frequency-sweep modulation [5]–[10] or coded by a pseudo random sequence [11]–[18], is transmitted in pulse compression. Then, the received signal is correlated with the reference signal that corresponds to the transmitted signal. The TOF of the reflected echo is determined from the peak in the correlated signal. In the proposed method, a maximum-length sequence (M-sequence), which is one of the binary pseudo random sequences, is used to code a transmitted signal.

Then, displacements of body surface are measured from the front and back of the human body. Each displacement is calculated from the TOF difference, which is estimated by tracking the phase difference of echo signals. The displacement by body movement is canceled by difference between the front and back displacements. Therefore, the small displacement by only breathing can be measured.

II. Method

A. Experimental setup

Experiments were conducted in an indoor environment. Measurement configuration is shown in Fig. 1. The volunteer stood at the distance of 1000 mm from front and back loudspeakers and microphones. Each distance between the loudspeaker and microphone was 80 mm. Loudspeakers and microphones were at a height of 1180 mm, and the volunteer was 1780 mm tall. M-sequence modulated signals were transmitted from loudspeakers (Pioneer PT-R4) and the reflected

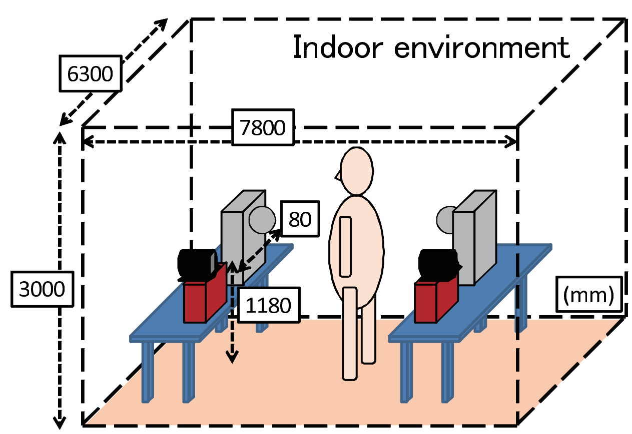

Fig. 1. Measurement configuration of experiment.

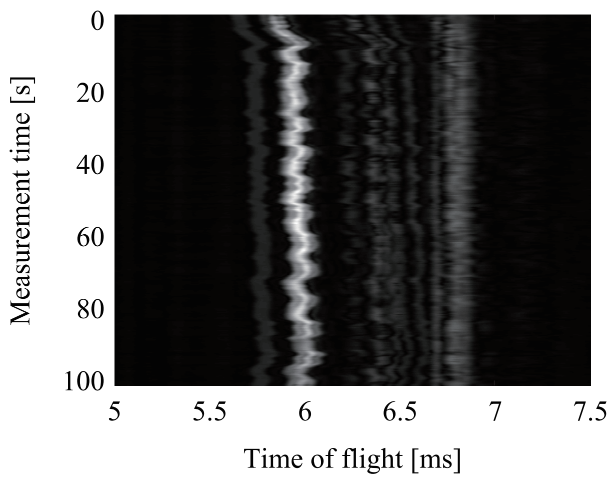

Fig. 2. M-mode image of echoes from the front surface.

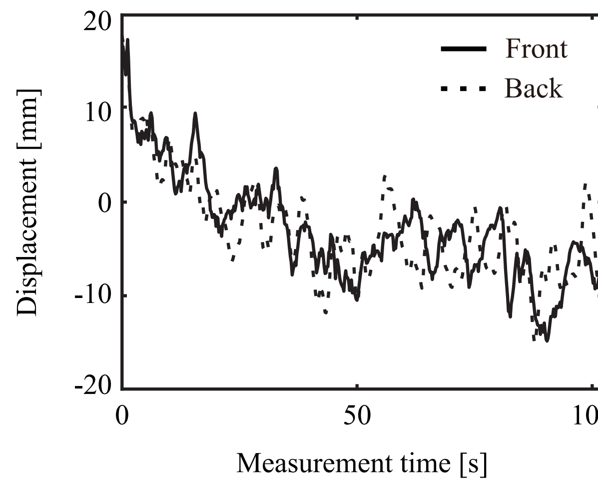

Fig. 3. Front and back displacements estimated from phase differences.

echoes were received by the microphones (B&K 4939). The interval and repetition of signal transmission were 0.2 s and 512 times. The received signal was amplified and filtered using a high-pass filter (HPF) with a cutoff frequency of 10 kHz. Then, the received signal was recorded at the sampling frequency of 250 kHz.

B. M-sequence pulse compression

An M-sequence is one of the binary pseudo random sequences generated from a linear feedback shift resister (LFSR). The order of the M-sequence is determined by the length of the LFSR. In the case of an nth-order M-sequence, $2^n - 1$ binary words consisting of 1 (True) and –1 (False) are sequentially generated from the LFSR. The SNR of an echo is theoretically improved by approximately $3 \times n$ dB.

In this paper, transmitted ultrasound was modulated by the 9th-order M-sequence, and 2 sine waves were assigned to 1 binary word of the M-sequence code. The carrier frequency of the M-sequence-modulated signal was 25 kHz. The wavelength of ultrasound was approximately 13.6 mm. The cycle length of the M-sequence-modulated signal was approximately 40.9 ms. 2 cycles of M-sequence-modulated signal was transmitted to remove the truncation noise.

III. Results and Discussion

The received signals were correlated with the reference signal which is discrete M-sequence code. The M-mode image of correlated signals of the front signals is illustrated in Fig. 2. Echoes reflected from the front of the human body can be observed around 6 ms. However, TOFs of echoes fluctuate by displacements by breathing and body movement. Displacements of the front and back of the body surface are illustrated in Fig. 3. Then, differences between the front and back displacements are illustrated in Fig. 4. The periodic displacement of several millimeters can be found. Therefore, the displacement by breathing seems to be measured by the proposed method. Furthermore, the Fourier transformed spectrum of the displacement of Fig. 4 is illustrated in Fig. 5. The breathing frequency was approximately 0.13 Hz.

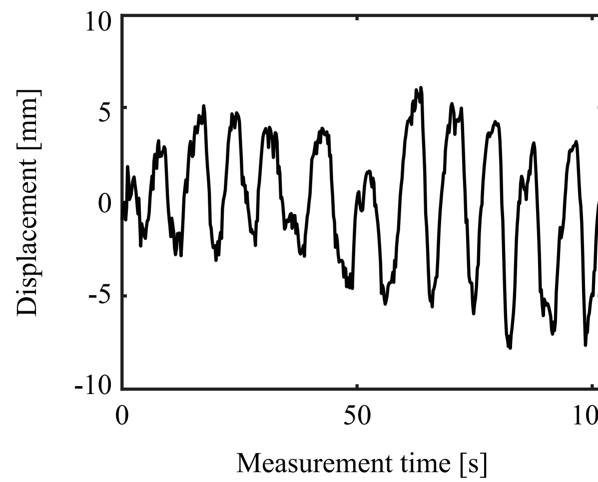

Fig. 4. Displacement between the front and back displacements.

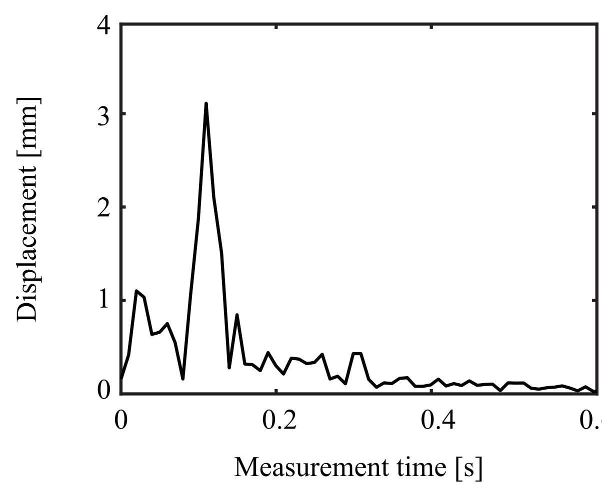

Fig. 5. Amplitude spectrum of displacement by breathing of Fig. 4.

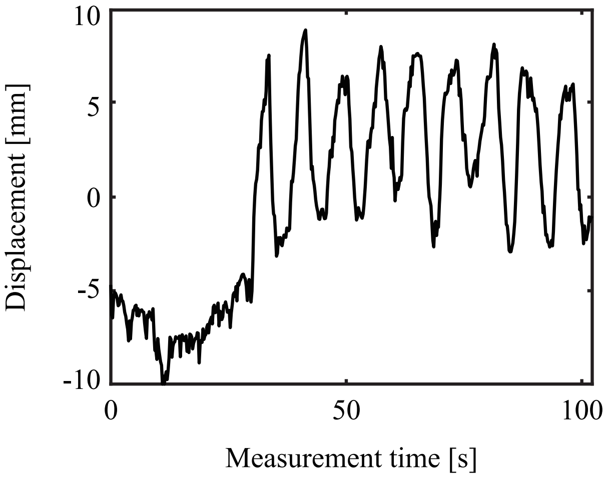

Fig. 6. Displacement between the front and back displacements.

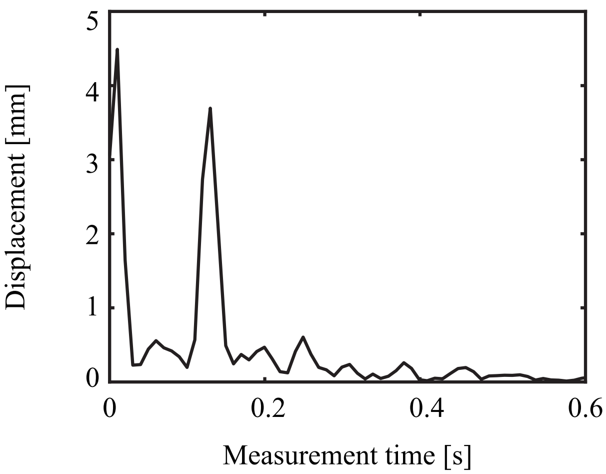

Fig. 7. Amplitude spectrum of displacement by breathing of Fig. 6.

For verification of the displacement by breathing, the volunteer was holding the breath during 30 seconds in the beginning of the experiment. After that, the volunteer started the breath. Differences between the front and back displacements are illustrated in Fig. 6. The displacement is smaller before the 30 seconds, and does not seem to be the displacement by breathing. Then, the periodic displacement starts after the 30 seconds. Therefore, this periodic displacement seems to be the displacement by breathing. Furthermore, the Fourier transformed spectrum of the displacement of Fig. 6 is illustrated in Fig. 7. The breathing frequency was also approximately 0.13 Hz, which is similar to that in Fig. 5.

IV. Conclusions

We have proposed non-contact measurement of human body surface displacement by breathing. First, the SNR of the echo reflected from the body surface is improved by M-sequence pulse compression. Then, displacements of the front and back of the human body are estimated by tracking phase differences of echo signals. After that, displacement by body movement is canceled by difference between the front and back displacements.

In this paper, the displacement by breathing of the standing volunteer was measured by the proposed method. When the volunteer is breathing, the displacement by breathing whose frequency was approximately 0.13 Hz could be measured.

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