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Study about accuracy of position and velocity measurement by multi-channel pulse compression using M-sequence modulated ultrasound

M系列変調超音波を用いた多チャンネルパルス圧縮による位置速度計測の精度検討

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1. Introduction

We have studied a method to measure the position and velocity of an object using ultrasound modulated by a maximum-length-sequence (M-sequence). In previous works, we have examined the accuracy of the proposed position and velocity measurement of a moving object using one transducer and microphone array [1, 2]. In this paper, we describe the position and velocity measurement by multi-channel pulse compression using two transducers and microphone array.

2. Position and velocity measurement using M-sequence modulated ultrasound

2.1. M-sequence pulse compression

In the proposed method, the position or velocity of an object is measured from an ultrasonic echo reflected from the object. To improve the signal-to-noise ratio (SNR) of the echo, pulse compression by an M-sequence is employed. An M-sequence is a binary pseudo random code composed of such as “1” and “-1”. The nth-order M-sequence is generated from the n-bit linear feedback shift register, and its length N is 2^n-1. The transmitted ultrasound is typically coded by modulating amplitude or phase corresponding to binary words. The SNR improvement for white noise is the square root of N times by correlation of the received signal with the reference signal corresponding to the transmitted signal.

2.2. Measurement for moving object

In the case of a moving object, the reflected echo is expanded or compressed by the Doppler effect. When the M-sequence modulated signal is Doppler-shifted, the signal cannot be correlated with the reference signal. In the proposed method, therefore, the reference signal also be Doppler-shifted based on Doppler shift measurement of the received signal. Furthermore, it is possible to estimate the Doppler velocity of the object.

2.3. Measurement using multi-transducer

In previous works, one transducer and microphone array are used for measurement. In the B-mode image formation by the synthesis aperture focusing technique, the aperture size, which determines the spatial resolution, can be expanded to add another transducer. When each transducer transmits alternately ultrasound modulated by an M-sequence, however, the flame rate of B-mode images is degraded. On the other hand, when all transducers transmit simultaneously ultrasound modulated by different M-sequences, the time resolution is not degraded. However, SNRs of the echoes are degraded by the interference noise. In this paper, the pair of M-sequences called preferred pair, that has the lower interference noise, is simultaneously transmitted. Then, the effect by the interference noise in the B-mode images are evaluated.

3. Experiment

3.1. Measurement configuration

The experimental setup of two transducers (sp1, sp2) and three microphones (mic1, mic2, mic3) is shown in **Fig. 1**. The object, which is an aluminum pole of 25 mm diameter, is moved by the linear stage at 360 mm/s. Transmitted signals are sine waves of 33.333 kHz modulated by the preferred-pair 11th-order M-sequence. When the object passes through (1220, 2070), transmission of ultrasound is started. After that, the measurement is done at 200 ms (72 mm) intervals. The experiments are done in two ways, at simultaneous transmission (ST) and non-simultaneous transmission (non-ST), to evaluate the effect by the interference noise. Furthermore, the reference path of the object is estimated from the measured positions when the object is stationary at 50 mm intervals.

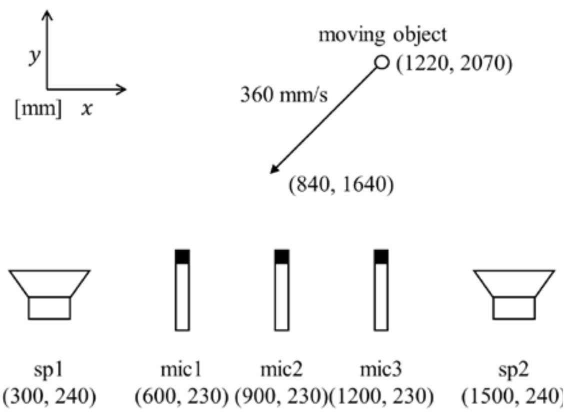
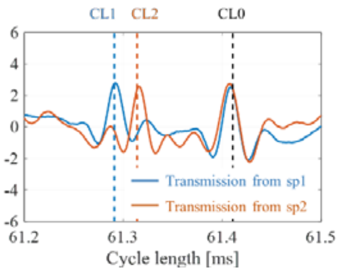
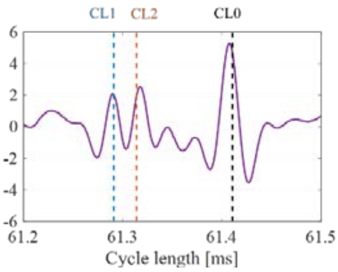


Fig. 1 Experimental setup.

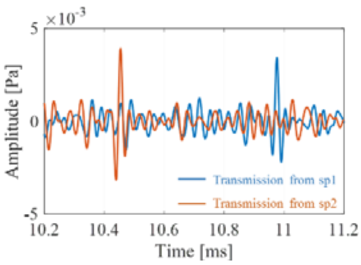


a) Non-ST

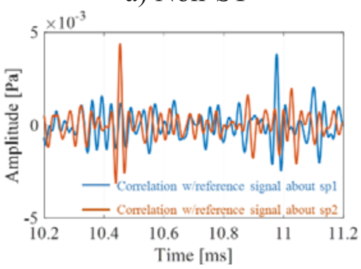


(b) ST

Fig. 2 Fourier-transformed amplitude spectrum of mic1.



a) Non-ST

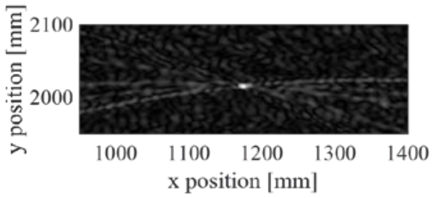


(b) ST

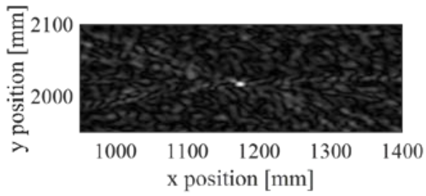
Fig. 3 Cross-correlation functions of mic1.

3.2. Experimental result

In the proposed method of the Doppler velocity measurement, the Doppler shift is estimated from the shift of the cycle length of the received M-sequence modulated signal. First, a moving target indication (MTI) filter was employed to remove the direct wave and echoes from stationary objects in the received signal. After that, the cycle length of Doppler-shifted M-sequence modulated signal was measured by the Fourier transform of amplitude spectrum. For example, **Fig. 2** shows the Fourier-transformed spectrum. The cycle lengths of M-sequence modulated signals are determined from the peak in the Fourier-transformed spectrum. The estimated cycle length at mic1 in non-ST and ST. Theoretical cycle lengths CL1, CL2 of signals transmitted from sp1, sp2 and cycle length CL0 of the original transmitted signal are shown in dashed lines.



a) Non-ST



(b) ST

Fig. 4 B-mode images around moving object.

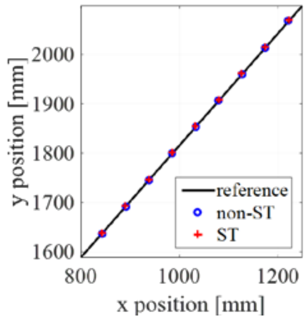


Fig. 5 Measured positions of moving object.

The reference signal was Doppler-shifted using peak value of **Fig. 2** nearest theoretical value. Cross-correlation functions by each reference signals are shown in **Fig. 3**. Correlation peaks corresponding to moving target could be observed both non-ST and ST. Thus, it is possible to measure position of moving object by the estimate of Doppler shift in proposed method. **Fig. 4** shows B-mode images formed from cross-correlation functions of mic1, mic2, mic3 by synthetic aperture focusing technique. **Fig. 5** shows positions of moving object determined from the pixel that their brightness is maximum.

4. Conclusion

In this paper, we described position and velocity measurement method by multi-channel pulse compression using two transducers and microphone array. In the case of ST, the interference noise occurred by simultaneous transmission of different M-sequences. However, the position of the moving object could be measured accurately both ST and non-ST.

References

1. S. Hirata, H. Hachiya: Jpn. J. Appl. Phys., Vol. 52, No. 7S, 07HC06, 2013.
2. Y. Ikari, S. Hirata, H. Hachiya: Jpn. J. Appl. Phys., Vol. 54, No. 7S1, 07HC14, 2015.