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POSITION AND VELOCITY MEASUREMENT OF A MOVING OBJECT BY PULSE COMPRESSION USING ULTRASOUND CODED BY PREFERRED-PAIR M-SEQUENCES

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To improve the SNR of the reflected echo, pulse compression using an M-sequence is employed in the pulse-echo method. In the case of a moving object, however, the echo is modulated owing to the Doppler effect. The Doppler-shifted M-sequence modulated signal cannot be correlated with the reference signal corresponding to the transmitted M-sequence modulated signal. Therefore, Doppler velocity estimation by spectrum-pattern analysis of a cyclic M-sequence modulated signal and cross correlations with Doppler-shifted reference signals corresponding to the estimated Doppler velocities has been proposed. Meanwhile, in the case of measurement using multiple transducers, the B-mode image can be formed from multipath cross-correlation functions. Then, the position of the object can be estimated from the B-mode image. When different ultrasound are simultaneously transmitted, preferred-pair M-sequence codes are typically used for coding ultrasound to avoid the crosstalk. In this paper, the position and velocity of the moving object are measured by using two loudspeaker and three microphones. Then, the effect of interference of two M-sequence modulated signals are evaluated by comparison between simultaneous-transmission and non-simultaneous-transmission.
Keywords: M-sequence, Pulse compression, Doppler shift

1. Introduction

The pulse-echo method based on the transmission of an ultrasonic pulse and time-of-flight (TOF) determination of the reflected echo is one of the typical methods of ultrasonic distance measurement [1-8]. To improve the signal-to-noise ratio (SNR) of the reflected echo and the resolution of the TOF, pulse compression is employed in the pulse-echo method [9, 10]. A signal with a sharp autocorrelation property, which is modulated by a frequency sweep [11-17] or coded by a pseudorandom sequence [18-27], is transmitted in pulse compression. Then, the received signal is correlated with the reference signal, which corresponds to the transmitted signal. In the cross-correlation function, the power of the reflected echo in the received signal is compressed as pulsive. Therefore, the TOF of the reflected echo is determined from the peak in the cross-correlation function.

A maximum-length sequence (M-sequence) is one of the pseudorandom sequences generated from a linear feedback shift register (LFSR) [23-27]. The M-sequence is used to code a transmitted signal for pulse compression. The amplitude or phase of the transmitted signal is typically modulated by binary words in the M-sequence code. When M-sequence codes of the reflected echo and the reference signal match, a high correlation value is obtained in the cross-correlation function. On the other hand, low correlation values are obtained when they do not match.

In the case of a moving object, however, the reflected echo is modulated owing to the Doppler effect. The Doppler shift of the echo is a linear expansion or compression in the time domain. Then, a high correlation value cannot be obtained even if M-sequence codes of the reflected echo and the

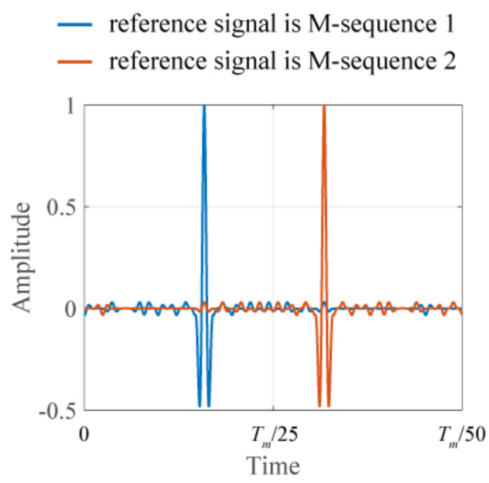

Figure 1: Cross-correlation functions of overlapped M-sequence codes and each M-sequence code.

reference signal match. To utilize pulse compression using an M-sequence in the case of moving object, we proposed Doppler velocity estimation by spectrum-pattern analysis of a cyclic M-sequence modulated signal [28]. Then, a high correlation value can be obtained by correlating with Doppler-shifted reference signals which correspond to the estimated Doppler velocities.

In the case of measurement using multiple transducers, the B-mode image can be formed from multipath cross-correlation functions. Then, the position of the object can be estimated from the B-mode image. However, the number of transducers are necessary to obtain an enough SNR and spatial resolution. For example, when different ultrasound are simultaneously transmitted, preferred-pair M-sequence codes are typically used for coding ultrasound to avoid the crosstalk. In this paper, therefore, the position and velocity of the moving object are measured by using two loudspeaker and three microphones. Then, the effect of interference of two M-sequence modulated signals are evaluated by comparison between simultaneous-transmission and non-simultaneous-transmission.

2. Method of position and velocity measurement

In this paper, ultrasound coded by preferred-pair M-sequences are transmitted from two loudspeaker. Then, the echo reflected from the moving object is received by three microphone. A preferred pair is the pair with the lower interference, low cross-correlation peaks. When the interference between transmitted signals becomes a problem, therefore, preferred-pair M-sequences are employed as codes. In the case of the preferred pair in 11th-order M-sequences, the cross-correlation function of overlapped M-sequence codes and each M-sequence code is illustrated in Fig. 1. T_m is code length of M-sequences. Both cross-correlation functions are almost not effected by the other M-sequence code.

In previous works, to estimate the Doppler velocity of the moving object, the spectrum pattern of each received signal is analysed [7, 28]. The Doppler velocity is obtained from Fourier transformation of the absolute amplitude spectrum. Fourier transformation of the absolute amplitude spectrum is equal to autocorrelation function. Therefore, autocorrelation function is employed to obtain the Doppler velocity in this paper. After that, the reference signal must be expanded or compressed proportionally with the estimated Doppler velocity. In this paper, the Doppler velocities corresponding to each loudspeaker are estimated from the signal received by each microphone. The received signal in each microphone is correlated with each Doppler-shifted reference signal corresponding to each microphone and each loudspeaker. Then, the TOF of Doppler-shifted echo is determined from the peak in the cross-correlation function. Each TOF corresponds to the path length from each loudspeaker to the moving object to each microphone. Therefore, a B-mode image can be formed from all cross-correlation functions by the synthetic aperture focusing technique. The position of the object is determined as the position of maximum brightness on this image.

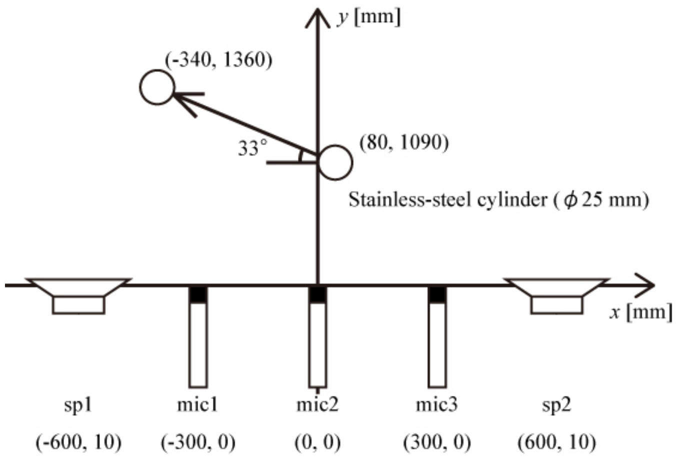

Figure 2: Experimental setup for position and velocity measurement.

3. Measurement configuration

The experimental setup for position and velocity measurement is illustrated in Fig. 2. The measurement system was composed three microphones and two loudspeakers. Positions of each microphone are mic1(600, 230), mic2(900, 230), and mic3(1200, 230), positions of each loudspeaker are sp1(300, 240) and sp2(1500, 240). The object was a stainless-steel cylinder whose diameter is 25 mm. The cylinder moved at a constant velocity on the linear motion stage. The speeds of the stage were set at 240 and 360 mm/s, the direction of the movement were set at -33◦. The transmitted ultrasound was coded by the 11th-order-M-sequences of the preferred pair to degrade the effect of the interference between two M-sequences as described previously. One sine wave was assigned to one binary word of the M-sequence. The carrier frequency of the M-sequence-modulated signal was 33.333 kHz. Therefore, the original cycle length of the transmitted signal was 61.41 ms. The interval of signal transmission was 0.2 s. The received signal was recorded at the sampling frequency of 2 MHz.

Before the Doppler velocity estimation, a moving target indication (MTI) filter was employed to remove non-Doppler signals, which are the direct wave and echoes from stationary objects. In the MTI filter, the previous received signal was subtracted from the present received signal. The Doppler velocity of the cylinder was estimated from the peak in each autocorrelation function. Then, each received signal was correlated with each Doppler-shifted reference signal. The B-mode image was formed from cross-correlation functions by the synthetic aperture focusing technique. The pixel pitch of the B-mode image was 0.1 mm. The position of the cylinder was determined as the position of maximum brightness on the image.

This experiment was done in two situations, simultaneous-transmission (ST) and non-simultaneous-transmission (NST). In the case of ST, two M-sequence modulated signals are transmitted simultaneously during the object is moving once. On the other hand, in NST, the object is moved twice. One M-sequence modulated signal is transmitted during the rst movement of the object. Moreover, the other M-sequence modulated signal is transmitted during the second movement of the object. Therefore, the effect of the interference of transmitted signals on the accuracy of position and velocity measurement was evaluated by comparing the result of ST with NST. In the case of ST, each received signal includes signals which were transmitted from sp1 and sp2 and whose Doppler shifts were different. Hence, two peaks appear in the autocorrelation function. Therefore, the TOF corresponding to the path length from each loudspeaker to the cylinder to each microphone is obtained from the cross-correlation function between each received signal and Doppler-shifted reference signal corresponding to each loudspeaker. Furthermore, in the case of ST, the B-mode image was formed from all six cross-correlation functions. In the case of NST, however, two B-mode images were formed from each three cross-correlation functions which were transmitted from each loudspeaker. The reason is to remove

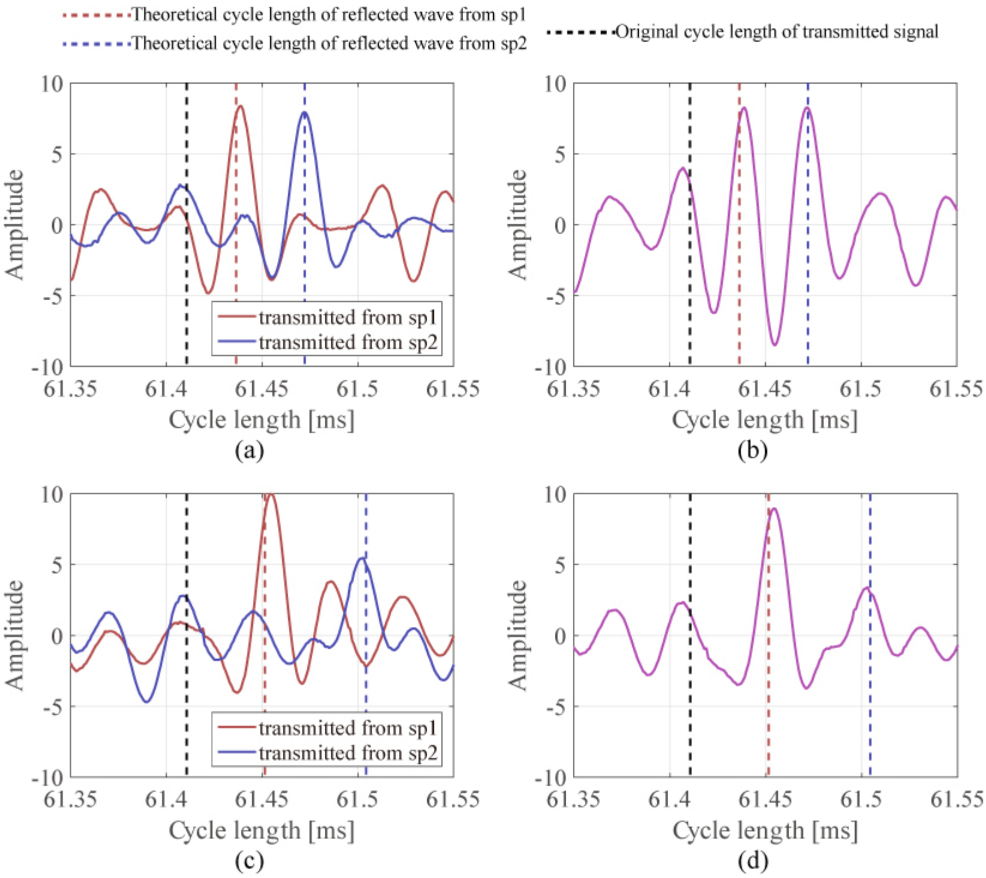

Figure 3: Autocorrelation functions of received signals when the target speed is 240 mm/s (a) (b), 360 mm/s (c) (d) in the case of NST (a) (c), ST (b) (d).

the effect of variability of the object movement.

4. Experimental results and discussion

Measurement was repeated 10 times at each path and each transmission method. Autocorrelation functions of received signals are shown in Fig. 3. In the case of NST, each estimated cycle length from two received signals transmitted from sp1 and sp2 is near theoretical cycle length. Moreover, in the case of ST, each estimated cycle length from one received signal is also near theoretical cycle length.

Cross-correlation functions of received signals and Doppler-shifted reference signals are shown in Fig. 4 In the case of ST, the noise level is higher than NST because of the effect of the interference of another transmitted signal. In either case, however, the echo reflected by the target could be obtained. The SNRs of the echo of NST and ST are 22.77 dB and 18.78 dB when the target speed is 240 mm/s. Furthermore, the SNRs of the echo of NST and ST are 22.30 dB and 18.66 dB when the target speed is 360 mm/s.

B-mode images formed from all cross-correlation functions are shown in Fig. 5. In the case of ST, the echoes reflected by the target are formed an image clearly as with NST. The SNRs of the B-mode image of NST and ST are 26.53 dB and 22.26 dB when the target speed is 240 mm/s. Moreover, the SNRs of the B-mode image of NST and ST are 25.57 dB and 21.11 dB when the target speed is 360 mm/s. The movement trajectory of the target and measurement positions are shown in Fig. 6. The movement trajectory is drawn based on measurement position of stationary target. In either case, NST and ST, measurement positions are near the movement trajectory. Therefore, simultaneous-transmission measurement using multi-transducer is possible as with non-simultaneous-transmission meas

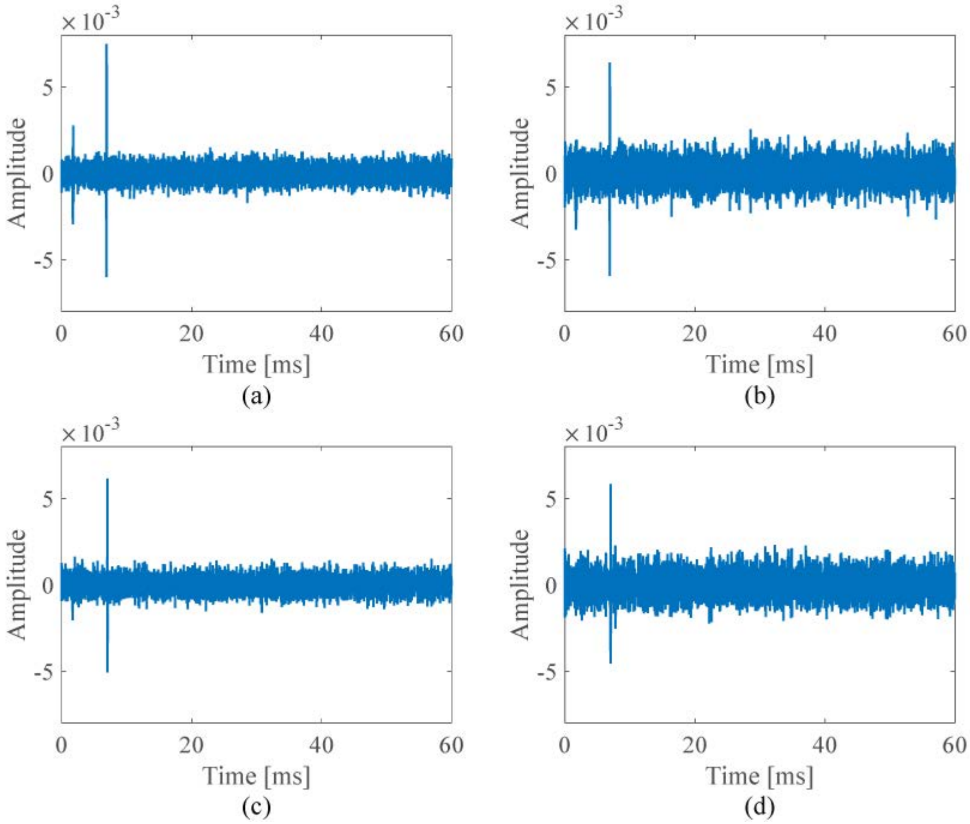

Figure 4: Cross-correlation functions of received signals and Doppler-shifted reference signals when the target speed is 240 mm/s (a) (b), 360 mm/s (c) (d) in the case of NST (a) (c), ST (b) (d).

urement in spite of the effect of the interference.

5. Conclusions

Doppler velocity estimation by spectrum-pattern analysis of a cyclic M-sequence modulated signal and cross correlations with Doppler-shifted reference signals corresponding to the estimated Doppler velocities has been proposed. In this paper, the position and velocity of the moving object were measured by using two loudspeaker and three microphones. The experiment was done in two situation, simultaneous-transmission (ST) and non-simultaneous-transmission (NST) of ultrasound coded by preferred-pair M-sequences. The effect of the interference of transmitted signals was compared between NST and ST. In the case of ST, SNRs of the echoes reflected by the target and B-mode images are lower than those of NST. In either case, however, position measurement was possible with high accuracy.

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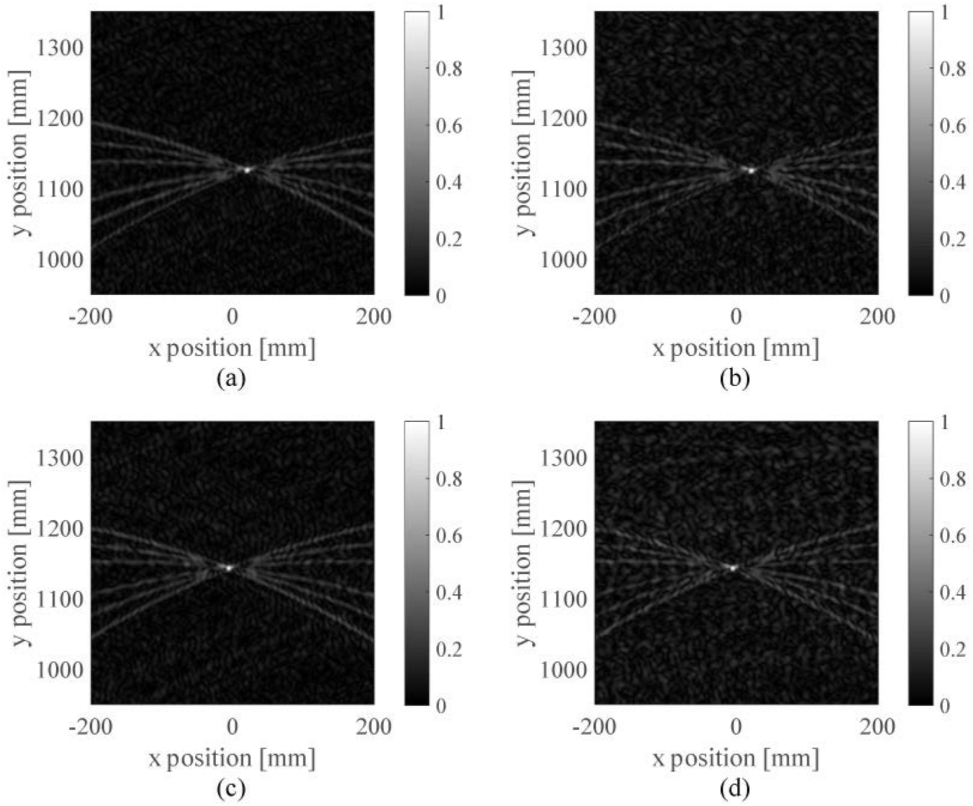

Figure 5: B-mode images around the target when the target speed is 240 mm/s (a) (b), 360 mm/s (c) (d) in the case of NST (a) (c), ST (b) (d).

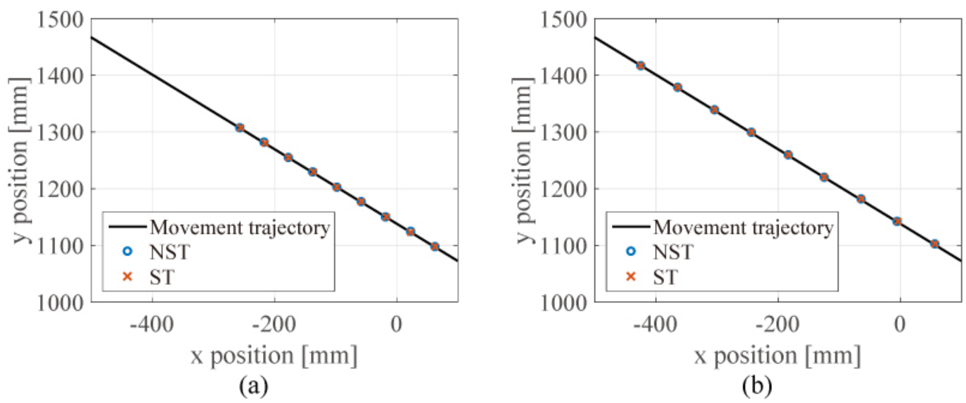

Figure 6: The movement trajectory of the target and measurement positions when the target speed is 240 mm/s (a), 360 mm/s (b).

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