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# Experimental verification of Doppler velocity estimation by spectrum pattern analysis of M-sequence modulated ultrasound
# M 系列変調超音波のスペクトルパターン解析を用いたドプラ速度計測の実験的検証

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## 1. Introduction

In ultrasonic mesurement of distance and velocity in air, we study pulse compression using M-sequence. In this method, the signal-to-noize ratio (SNR) of the reflected echo and distance resolution can be improved by correlation of the received signal with the reference signal[1].

In the case of a moving object, however, the reflected echo is modulated due to the Doppler effect. The Doppler-shifted echo cannot be correlated with the reference signal. The distance to the moving object can be estimated from correlation of the received signal with the Doppler-shifted reference signal. Therefore, Doppler velocity estimation from spectrum pattern of cyclic M-sequence modulated signal has been proposed[2]. In this report, we verify the effect of environment noize in the proposed Doppler velocity estimation.

## 2. Principle of Doppler velocity estimation by spectrum pattern analysis

The amplitude spectrum of cyclic *n*th-order M-sequence modulated signal is given by

$$S_m(f) = \frac{\sqrt{N+1}}{N}\frac{\sin\{\pi(f+f_c)T_d\}}{\pi(f+f_c)T_d} \sum_{k=-\infty,\neq -T_m\cdot f_c}^{\infty}\delta\left(f-\frac{k}{T_m}\right)+\frac{1}{N}\delta(f+f_c) + \frac{\sqrt{N+1}}{N}\frac{\sin\{\pi(f-f_c)T_d\}}{\pi(f-f_c)T_d} \sum_{k=-\infty,\neq T_m\cdot f_c}^{\infty}\delta\left(f-\frac{k}{T_m}\right)+\frac{1}{N}\delta(f-f_c). \quad (1)$$

$f_c$ is the frequency of carrier waves, $T_d$ is the time of 1 digit in the M-sequence modulated signal, $T_m$ is cycle length of the M-sequence modulated signal, and $N$ is the sequence length of the M-sequence which is given by $2^n-1$. This spectrum is expressed as a summation of delta functions whose interval is inverse of the cycle length. Therefore, the cycle length of the M-sequence modulated signal can be estimated by the Fourier transformation of this spectrum.

The Doppler shift of the cycle length is corresponding to the Doppler velocity of the moving object. The Doppler velocity is given by

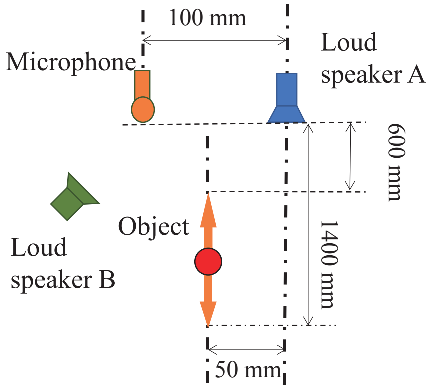

Fig. 1 Experimental setup for verification of Doppler velocity estimation.

$$v_d = \frac{T_m-T_s}{T_m+T_s}c. \quad (2)$$

$T_m$ is the initial cycle length, $T_s$ is the Doppler-shifted cycle length, and $c$ is an ultrasonic propagation velocity in air.

## 3. Measurement configuration

The experimental setup is illustrated in **Fig. 1**. The microphone was arranged at a distance 100 mm from the loud speaker A. The object was arranged at a center of the loud speaker A and the microphone in a lateral direction. Then, the object moved from 600 mm to 1400 mm in a vertical direction at a constant speed. In the experiments, the transmitted ultrasound was modulated by the 10th-order M-sequence, and 1 sine was assigned to 1 digit of the M-sequence. The carrier frequency of the transmitted signal was 40 kHz. Therefore, the initial cycle length was 25.575 ms. 2-cycles of the M-sequence modulated signal was transmitted from the loud speaker A. The received signal was recorded every 0.1 s by the sampling frequency of 4 MHz. Then, a moving target indication (MTI) filter is employed to subtract non-Doppler signals which are the direct wave and echoes from static objects. After that, the Doppler-shifted cycle length of the M-sequence modulated signal and the Doppler velocity of the moving object were estimated.

The SNRs of the received signals were changed

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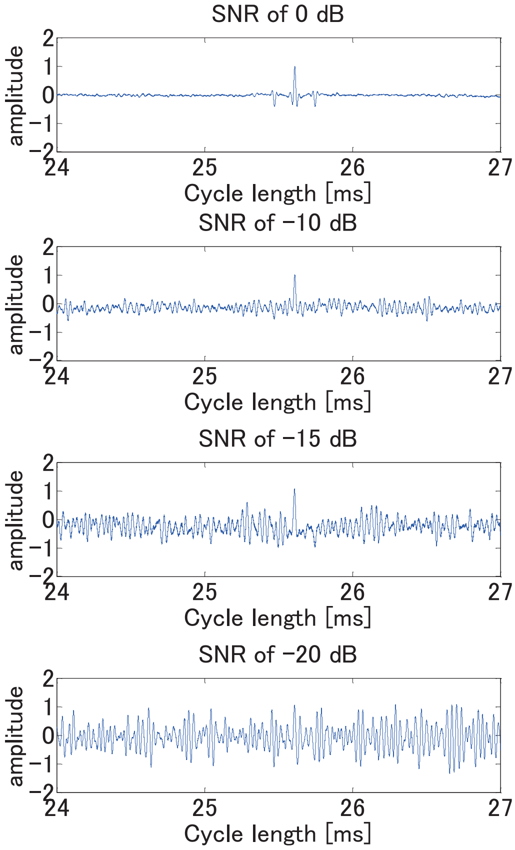

Fig. 2 Results of spectrum pattern analysis of received signals after the MTI filter.

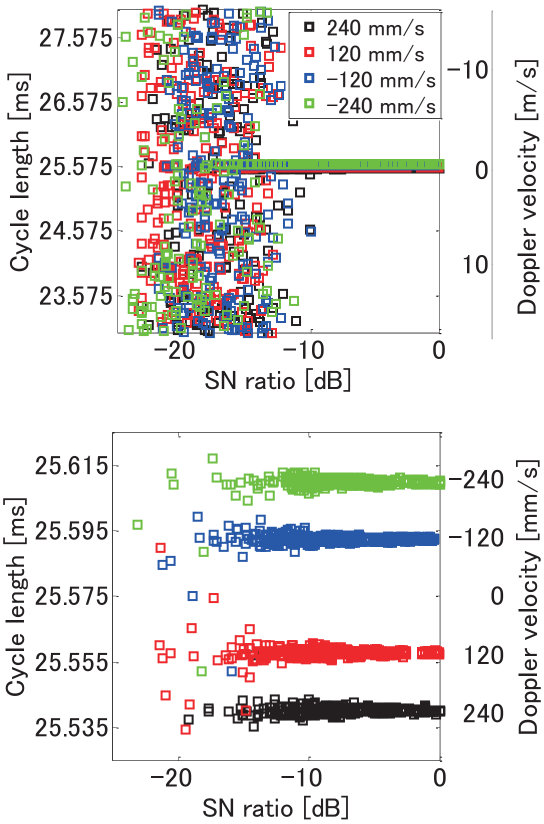

Fig. 3 Estimated cycle lengths and Doppler velocities and their close-up view.

by transmission of a white noise from loud speaker B. The amplitudes of reflected echoes increase as the target comes close to the loud speaker A and the microphone. Therefore, the SNR of the received signal was estimated from the echo amplitude and the standard deviation of the noise in each measurement. The SNRs of the received signals were set from approximately -25 dB to 0 dB. The object was a column of polystyrene. The diameter of the object was 25 mm. The speeds of the object were set at 240 mm/s, 120 mm/s, -120 mm/s, 240 mm/s. In each speed of the object, the Doppler velocities were estimated in 50-times measurements.

## 4. Experimental result

When the speed of the moving object is 240 mm/s, the results of spectrum pattern analysis of the received signals are illustrated in **Fig. 2**. In case the SNRs are more than -10 dB, the peak amplitudes which are corresponding to the Doppler-shifted cycle lengths seem to be larger than the noise levels. In the case of -15 dB, however, the peak amplitude approaches to the noise peaks. In the case of -20 dB, then, determination of the peak has become impossible.

The estimated cycle lengths and Doppler velocities are illustrated in **Fig. 3**. In case the SNRs are more than -10 dB, the Doppler velocities could be estimated with no significant errors in all speeds. In case the SNRs are less than -15 dB, then, it was almost difficult to estimate Doppler velocities.

## 5. Conclusion

We have proposed the Doppler velocity estimation on pulse compression using the M-sequence modulated signal. The Doppler velocity estimation in a noisy environment is verified in this report. In this proposed method, accuracy of a noisy environment is determined by the length of M-sequence modulated signal and measurement rate. When the measurement rate is 10 Hz and the length of M-sequence modulated signal is 51.15 ms, the Doppler velocities could be estimated with no significant errors in all speeds when the SNRs of the received signals were more than -10 dB. In the future work, we will verify the effect of the cycle length or the carrier frequency of the M-sequence modulated signal.

## References

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