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Precise ultrasonic distance measurement of moving object by using single Linear-Period-Modulated signal independent of Doppler velocity estimation

ドプラ速度推定に依存しない LPM 信号を用いた移動物体の超音波距離計測

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1. Introduction

Ultrasonic distance measurement by using pulse echo method is based on the time interval from transmission time of the pulse to received time of the echo reflected from the target(Time of Flight: TOF). Moreover, pulse compression of chirp signal by cross correlation is effective to reduce white noise and improve distance resolution.

Linear-Period-Modulated/Hyperbolic-Frequency-Modulated signal (hereinafter referred to LPM signal): a kind of chirp signal is Doppler tolerant. Therefore significant peaks of cross correlation function of LPM signal can be obtained even if the echo is modulated by Doppler effect, and this property is suitable for distance measurement of moving object. Although LPM signal is Doppler tolerant, TOF is affected by Doppler shift of period and phase of the echo. In the previous study, Doppler velocity estimation of the target is required to compensate the errors of TOF.[1, 2]

Thus, in this study, we propose distance measurement method that get rid of the errors of TOF due to Doppler shift of period. In this method, the errors of TOF due to Doppler effect can be compensated without velocity estimation. In this paper, principle of the method is described and the method is evaluated by numerical simulation.

2. Principle of the proposed method

2.1 Errors of TOF due to Doppler shift

On the pulse echo method that using cross correlation of LPM signal, calculated TOF varies in response to Doppler velocity of the target. The variation amount is sum of ΔTOF_1 and ΔTOF_2 caused by Doppler shift of period and phase of the echo respectively. The previous method requires Doppler velocity estimation to compensate ΔTOF_1.

ΔTOF_1 is expressed as

$$\Delta TOF_1 = p_s \frac{l_0}{p_b} \cdot \frac{2v_d}{v_0 + v_d} \qquad (1)$$

where v_0 is velocity of sound, v_d is Doppler velocity of the target. p_s is period of wave front, l_0 is length, and p_b is chirp width of transmission signal.

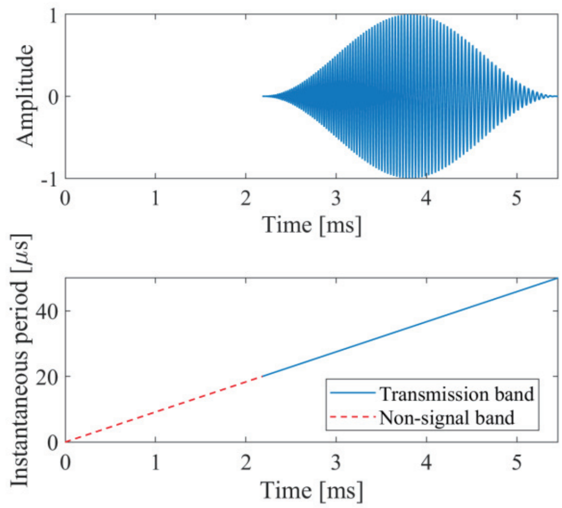

Fig.1 Waveform and instantaneous period of transmission signal

2.2 Error compensation of TOF independent Doppler velocity estimation

According to **Eq.(1)**, ΔTOF_1 is always zero regardless of v_d when p_s is zero. This means wave front of the transmission signal (reference signal) always correspond to the echo since p_s is invariant. However, it is impossible to transmit high frequency signal such as period is zero, therefore these band of LPM signal are set non-signal state on transmission. In principle, TOF is unchanged even if the part of LPM signal is non-signal state. Waveform of transmission signal is shown in upper part of **Fig.1**, and the lower part represents instantaneous period of the signal. The broken/solid line means non-signal/transmission band.

Since ΔTOF_1 is null, only compensation of ΔTOF_2 is required. ΔTOF_2 is occurred by phase differences on the band that period of the reference signal correspond to period of the echo. ΔTOF_2 can be compensated by regarding maximum peak time of envelope of complex cross correlation function as TOF.[1] The transmission signal is amplitude modulated with Hann window to reduce distortion of the envelope as shown in Fig.1.

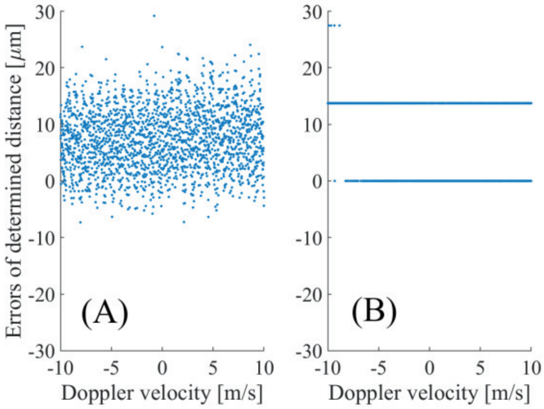

Fig.2 Measurement errors of 1 m + 1.867 μm that integer multiple of resolution
(A): Previous method, (B): Proposed method

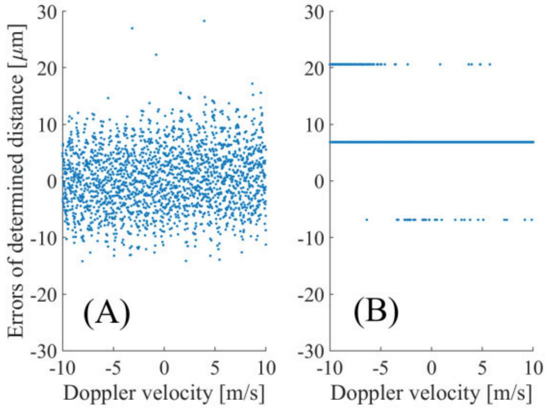

Fig.3 Measurement errors of 1 m + 8.735 μm that half-integer multiple of resolution
(A): Previous method, (B):Proposed method

3. Evaluation

3.1 Simulation conditions

In order to verify the proposed method, measurement errors of the proposed method were compared with previous method by numerical simulation. v_0 was 343.4 m/s, sampling frequency was 12.5 MHz, and the observer and the target were placed in noiseless environment. Least Significant Distance (LSD) of the measurement depends on v_0 and sampling frequency, and LSD of this simulation was 13.74 μm. The echo that received by the observer was modulated to single-bit signal by 7-th order Delta-Sigma modulator, then the cross correlation function was calculated by single-bit signal processing. The cross correlation function was filtered by triangular moving average filter to smooth noises associated with single-bit modulation. The filter length was 141 taps (previous method), 713 taps (proposed method) respectively.

3.2 Results

In this section, considering the condition that a moving object measured by stationary observer. v_d was varied from -10 to 10 m/s at 0.01 m/s step, and the distance was measured at every velocity. The determined distance means the distance between the observer and the target when wave front of the transmission signal reached target.

Errors of the determined distance when the true distance was integer / half-integer multiple of resolution (1 m + 1.867 μm / 1 m + 8.735 μm) are shown in **Fig. 2, 3** respectively. In both results, the errors distributed around ±1 LSD. From these results, we confirmed that proposed method has resolution equivalent to previous method. While the errors of proposed method concentrated on constant value in range ±1 LSD, partially maximum error was ±2 LSD. The causes of increase of the error were distortion of cross correlation function due to decrease of corresponded length of reference signal and the echo, and discrete time simulation.

4. Advantage of proposed method

Since the previous method depends on Doppler velocity estimation, measurement value was affected by the error of estimated velocity, and apparent distance resolution was higher than actual since compensation amount was smaller than LSD.

On the other hand, proposed method was not affected by Doppler velocity, and step of the measurement value correspond to LSD. Therefore, proposed method is more efficient and stable compared with previous method.

5. Conclusion

Ultrasonic distance measurement of moving object by using LPM signal that enable Doppler shift compensation of TOF independent Doppler velocity estimation was proposed. Furthermore, the proposed method has advantages on efficiency of measurement process and stability of measurement result.

References

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