

Ultrasonic distance and velocity measurement by low-calculation-cost Doppler-shift compensation and high-resolution Doppler velocity estimation with wide measurement range

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1. Introduction

Ultrasonic sensing systems have been studied for measurement of distance or velocity [1–3]. The pulse-echo method is one of the typical methods of ultrasonic distance measurement. The pulse-echo method is based on determination of the time of flight (TOF) of an echo reflected from an object. For improvement of the signal-to-noise ratio (SNR) of the reflected echo and distance resolution, pulse compression has been introduced in the pulse-echo method [1]. However, real-time distance measurement by pulse compression is difficult because of the high-calculation-cost digital signal processing for cross-correlation of the received signal and the reference signal. To reduce the calculation cost of cross correlation, a sensor signal processing method using a delta-sigma modulated single-bit digital signal has been proposed [4]. The proposed recursive cross-correlation operation of single-bit signals can reduce the calculation cost of cross-correlation.

In the case of a moving object, the reflected echo is modulated due to the Doppler effect. The Doppler effect on the reflected echo brings about decrease or increase in the signal period in proportion to the Doppler velocity of the object. Pulse compression using a linear-period-modulated (LPM) signal has been proposed for distance measurement of a moving object [2]. The cross-correlation function of the Doppler-shift LPM signal and the reference LPM signal is also modulated due to the Doppler effect. Therefore, the distance of the moving object is estimated from the envelope of the cross-correlation function. However, cross correlation with a complex reference signal to obtain an envelope of the cross-correlation function increases the calculation cost of the digital signal processing. The distance and velocity measurement of a moving object using a pair of LPM signals, which includes an up-chirp LPM signal and a down-chirp LPM signal, has been proposed [3]. However, cross correlation with two reference LPM signals also increases the calculation cost. Furthermore, the velocity of a moving object is estimated from the phase of the peaks in the cross-correlation function.

Therefore, measurement range of the velocity is limited due to the transmitted LPM signal.

In this paper, low-calculation-cost Doppler-shift compensation and high-resolution Doppler velocity estimation with wide measurement range are proposed. A pair of LPM signals, which includes two down-chirp LPM signals, is transmitted in the proposed method. The received signal is correlated with the single reference LPM signal using cross-correlation by single-bit signal processing. The distance and the Doppler velocity of the object are estimated from the modulated cross-correlation function with the low calculation cost.

2. Doppler-shift compensation

In the case of a non-Doppler effect, the TOF of the received LPM signal is typically estimated from the maximum peak time in the cross-correlation function. In the case of a moving object, however, the cross-correlation function for estimation of the TOF of the received LPM signal is modulated due to the Doppler effect, as illustrated in Fig. 1.

The Doppler effect on the wave form of the modulated cross-correlation function is caused by the phase shift of the received LPM signal. Therefore, the maximum peak time in the modulated cross-correlation function does not show the TOF of the received LPM signal. The peak time in the envelope of the cross-correlation function is required to estimate the TOF of the received LPM signal. In the proposed method, the peak time t_p in the envelope of the cross-correlation function can be estimated from the maximum peak time t_{\max} , the minimum peak time t_{\min} , and their absolute amplitudes $|p_{\max}|$ and $|p_{\min}|$ in the modulated cross-correlation function obtained from single-bit signal processing. If the phase shift of the cross-correlation function is null, the ratio of $|p_{\max}|$ to $|p_{\min}|$ is 1.4285 and the peak time t_p in the envelope of the cross-correlation function is t_{\max} . If the phase shift of the cross-correlation function is $\pm 90^\circ$, the ratio of $|p_{\max}|$ to $|p_{\min}|$ is 1 and the peak time t_p in the envelope of the cross-correlation function is the halfway point between t_{\max} and t_{\min} . If the phase shift of the cross-correlation function is $\pm 180^\circ$, the ratio of $|p_{\max}|$ to $|p_{\min}|$ is $1/1.4285$ and the peak time t_p in

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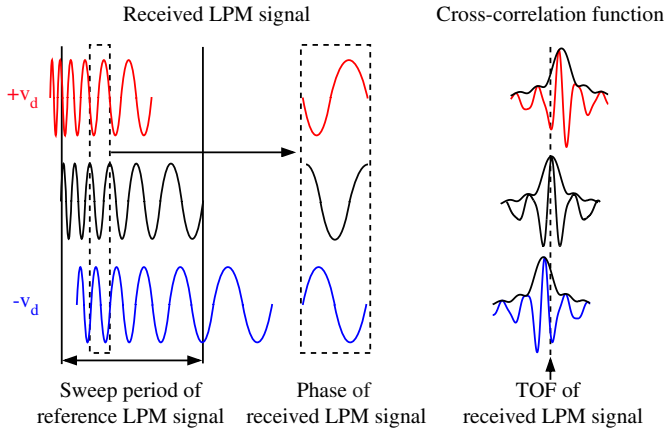


Fig. 1 Doppler effect on the received LPM signal and cross-correlation function.

the envelope of the cross-correlation function is t_{\min} . By a first-order approximation of the ratio shift of absolute amplitudes, the peak time t_p in the envelope of the cross-correlation function can be expressed as, if $|p_{\max}| > |p_{\min}|$,

$$\begin{cases} r_{\max} = 0.5 \cdot \frac{\left| \frac{p_{\max}}{p_{\min}} \right| - 1}{1.4285 - 1} + 0.5 \\ r_{\min} = 1 - r_{\max} \end{cases}, \quad (1)$$

and if $|p_{\max}| < |p_{\min}|$,

$$\begin{cases} r_{\max} = 1 - r_{\min} \\ r_{\min} = 0.5 \cdot \frac{\left| \frac{p_{\min}}{p_{\max}} \right| - 1}{1.4285 - 1} + 0.5 \end{cases}, \quad (2)$$

$$t_p = r_{\max} \cdot t_{\max} + r_{\min} \cdot t_{\min}, \quad (3)$$

where r_{\max} is the coefficient value of t_{\max} , and r_{\min} is the coefficient value of t_{\min} .

The peak time t_p in the envelope of the cross-correlation function is shifted from the TOF of the received LPM signal. The Doppler effect on the peak time in the envelope of the modulated cross-correlation function is caused by the sweep period shift of the received LPM signal. The Doppler-shift time t_d of the peak time t_p can be expressed as

$$\begin{aligned} t_d &= \frac{p_0 - p_{0d}}{p_b} \cdot l_0 \\ &= \frac{v_d}{v + v_d} \cdot \frac{p_0}{p_b} \cdot l_0, \end{aligned} \quad (4)$$

where p_0 is the starting period of the reference LPM signal, p_{0d} is the starting period of the Doppler-shift LPM signal, and p_b is the sweep period band of the reference LPM signal. Meanwhile, v_d is the Doppler velocity of the object, v is the propagation velocity of an ultrasonic wave in air, and l_0 is the length of the reference LPM signal. The TOF of the received LPM signal can be estimated by subtraction of the Doppler-shift time t_d estimated in Eq. (4) from the peak time t_p estimated in Eq. (3). The proposed Doppler-shift compensation can thus determine the distance of the moving object with low-calculation-cost by numerical calculation alone.

3. Doppler velocity estimation

Doppler velocity estimation of a moving object is required for the proposed Doppler-shift compensation. The pulsed Doppler method is one of the typical methods of Doppler velocity estimation. In the pulsed Doppler method, the Doppler velocity is estimated from the Doppler-shift frequency, which is given by the Fourier transform of the echo reflected from the moving object. Velocity resolution by the Fourier transform is not sufficient for the proposed Doppler-shift compensation, however, because of the short length of the ultrasonic pulse. In case the period of the transmitted LPM signal sweeps from 20 μ s to 50 μ s in 3.274 ms, resolution of the Doppler velocity is approximately 2.12 m/s.

Furthermore, measurement range of Doppler velocity estimation from the phase of the peaks in the cross-correlation function is limited because the measurement range of the phase is $\pm 180^\circ$. In case the period of the transmitted LPM signal sweeps from 20 μ s to 50 μ s in 3.274 ms, measurement range of the Doppler velocity is approximately ± 1.58 m/s.

The length of the received LPM signal is linearly decreased or increased due to the Doppler effect. When a pair of LPM signals is transmitted, the cross-correlation function of the pair of LPM signals and the single reference LPM signal has two peaks. The interval of the first peak and the second peak of the cross-correlation function shows the length of the single LPM signal. The cross-correlation function of the pair of Doppler-shift LPM signals and the single reference LPM signal also has two peaks. The interval of the first maximum peak and the second maximum peak in the modulated cross-correlation function shows the Doppler-shift length of the single LPM signal. The Doppler-shift length of the single LPM signal is expressed as

$$l_d = \frac{v_d}{v + v_d} \cdot l_0, \quad (5)$$

where l_d is the Doppler-shift length of the single LPM signal, l_0 is the length of the single LPM signal, v_d is the Doppler velocity, and v is the propagation velocity of an ultrasonic wave in air.

Time resolution of the Doppler-shift length of the single LPM signal estimated from the cross-correlation function obtained by single-bit signal processing is improved by high-sampling-frequency signal processing. Therefore, the Doppler velocity can be estimated with sufficient velocity resolution. In case the length of the single LPM signal is 3.274 ms and sampling frequency is 50 MHz, resolution of the Doppler velocity is approximately 0.0085 m/s with wide measurement range.

4. Distance and velocity measurement

The proposed method of distance and velocity measurement by pulse compression using a pair of LPM signals and Doppler-shift compensation is illustrated in Fig. 2. In the proposed method, a pair of LPM signals is transmitted by a loudspeaker. The received signal of a microphone is converted into a single-bit received signal by a delta-sigma modulator. The single reference LPM signal is converted into a single-bit reference signal by a digital comparator. The cross-correlation function of the received signal and the

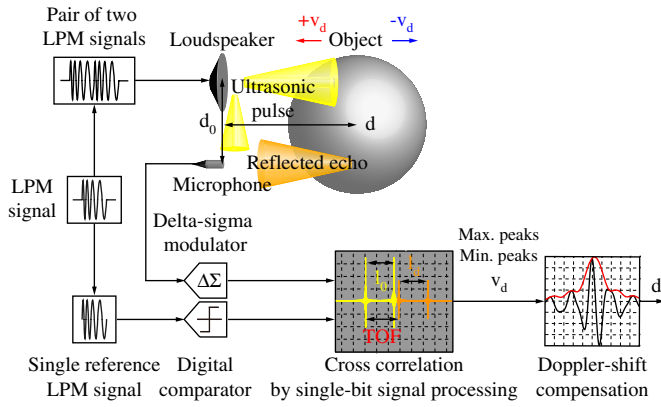


Fig. 2 Design of the proposed method of ultrasonic distance and velocity measurement by pulse compression using a pair of LPM signals and applying Doppler-shift compensation.

reference signal is obtained from a recursive cross-correlation operation of single-bit signals and a smoothing operation accomplished by a weighted moving average filter [4]. The distance and velocity of the object is determined by the proposed method.

The proposed method was evaluated by a computer simulation using MATLAB. In the simulation, the period of the single LPM signal linearly swept from $20\mu\text{s}$ to $50\mu\text{s}$. The length of the single LPM signal was 3.274 ms , and the length of the pair of LPM signals was 6.548 ms . The distance to the object was 1.000 m , when the pair of LPM signals was transmitted. The propagation velocity of an ultrasonic wave in air is 346.7 m/s at 25°C . The sampling frequency of delta-sigma modulator was 50 MHz . The length of the weighted moving average filter for the smoothing operation was 217 taps. The weights of the filter are given by the triangular function.

In the proposed Doppler velocity estimation, the Doppler velocity was estimated from the interval of the first maximum peak and the second maximum peak in the modulated cross-correlation function, as illustrated in Fig. 3(a). For comparison, the Doppler velocity estimated by the pulsed Doppler method, and the Doppler velocity estimated from the phase of the peaks in the modulated cross-correlation function are also indicated in Fig. 3(a). Velocity error of the proposed Doppler velocity estimation is illustrated in Fig. 3(b). The Doppler velocity can be determined with high resolution and wide measurement range by the proposed Doppler velocity estimation.

In the proposed Doppler-shift compensation, the peak time t_p in the envelope of the modulated cross-correlation function was estimated by a first-order approximation of the ratio shift of absolute amplitudes. The Doppler-shift time t_d was estimated from the estimated Doppler velocity. The distance of the object determined by subtraction of the Doppler-shift time t_d from the peak time t_p is illustrated in Fig. 4(a). Distance error of the proposed Doppler-shift compensation is illustrated in Fig. 4(b). For comparison, the peak time t_{p0} in the envelope of the cross-correlation function was also estimated by cross correlation with a complex

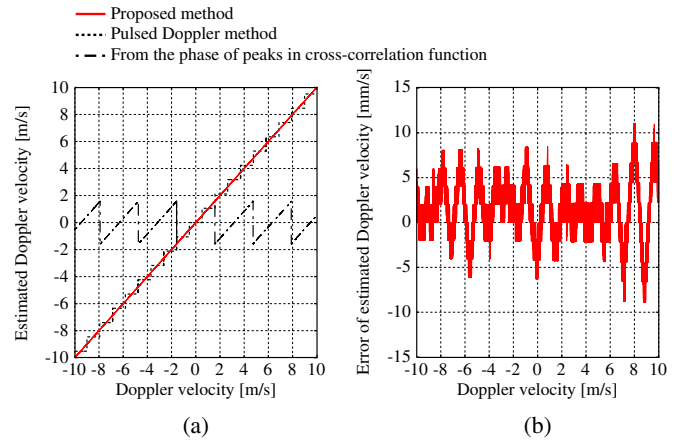


Fig. 3 Simulation results of Doppler velocity compensation.

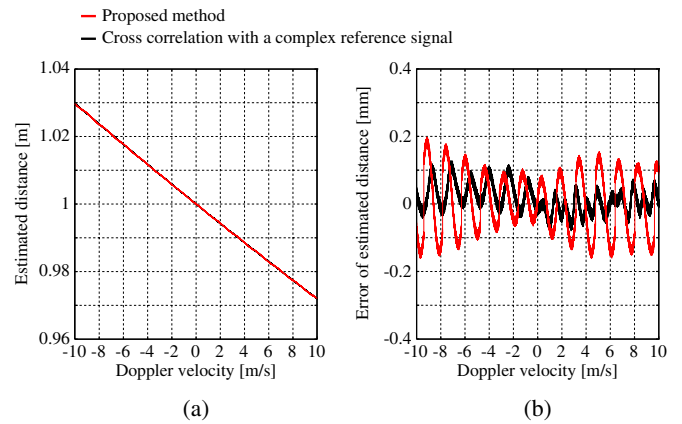


Fig. 4 Simulation results of Doppler-shift compensation.

reference signal. The distance of the object determined by subtraction of the Doppler-shift time t_d from the peak time t_{p0} is also indicated in Fig. 4(a). Distance error of the typical Doppler-shift compensation by cross correlation with a complex reference signal is illustrated in Fig. 4(b). The distance determined by the proposed method includes distance error of $\pm 0.2\text{ mm}$, however, the distance can be determined by the proposed Doppler-shift compensation with the low calculation cost.

5. Conclusion

A low-calculation-cost Doppler-shift compensation and high-resolution Doppler velocity estimation with wide measurement range are proposed. In the proposed method, a pair of LPM signals is transmitted, and then correlated with a single reference LPM signal. The Doppler velocity of the object can be estimated from the interval of the first maximum peak and the second maximum peak in the modulated cross-correlation function with high resolution and wide measurement range. The distance can be determined from the peak time in the envelope of the modulated cross-correlation function is estimated by a first-order approximation of the ratio shift of absolute amplitudes with the low calculation cost.

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