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Speed Measurement of Moving Object by Using Sensitivity Compensated Ultrasonic Transmitting Signal and Pulse Compression

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ABSTRACT

Target ranging methods using ultrasonic pulse-echo are widely employed for remote sensing of automobiles and robots etc., but the accuracy is not sufficient for measuring the moving speed of the target instantly. In order to acquire compression pulse with both high resolution and high signal to noise ratio (SNR), a method using a sensitivity compensated transmitting (SCT) signal and pulse compression was proposed. To receive an ultrasonic echo signal with a broader bandwidth and a flatter spectrum, the SCT signal is calculated by inversing the spectrum of the response function majorly composed of the sensitivities of transmitters and receivers. In this paper, an approach of speed measurement using the SCT signal is studied. The results of primary experiments indicate a possibility of the application of low speed measurement by using ultrasonic pulse-echo method.

INTRODUCTION

Target ranging methods using ultrasonic pulse-echo are widely employed for remote sensing of automobiles and robots etc. To augment both the range resolution and the signal to noise ratio (SNR), pulse compression techniques using coded pulses with long durations, such as phase coding [1] or frequency modulation [2], are employed. But the accuracy is not sufficient for application of measuring the moving speed of the target instantly. Instead, Doppler shift of the frequency is commonly used for speed measurement with ultrasonic pulse-echo method. However, owing to the resolution of the frequency shift, the measurable low speed is limited.

In order to acquire compression pulse with both high resolution and high SNR, we proposed a new method for target ranging with ultrasonic pulse-echo method, using a sensitivity compensated transmitting (SCT) signal derived by inverse filtered processing and pulse compression using a matched filtered processing [3]. It was verified experimentally that the effective spectrum of received echo signal using SCT signal is flatter and broader than that using normal linear frequency-modulated (FM) Chirp wave as transmitting signal. Furthermore, the resolution of the compressed pulse is higher than that using the Chirp wave as transmitting signal and matched filtered pulse compression, while the SNR of the compressed pulse is higher than that using the Chirp wave as transmitting signal and inverse filtered pulse compression.

In this paper, the approach of speed measurement using the SCT signal and pulse compression is studied. Two ultrasonic transducers with 40 kHz resonant frequency are employed. First, with a direct transmitting-receiving arrangement of transducers, using a linear FM Chirp wave as the transmitting signal, a reference signal, whose spectrum depends mainly on the sensitivities of ultrasonic transducers, is measured. The SCT signal is calculated from the quotient of spectra of the Chirp wave and its reference received signal by inverse filtered processing. Then, a 7 cm × 7 cm steel plate with about 1 m distance from the transducers is employed as measuring target. By using the SCT signal, the received echo signal shows an effective flat spectrum between 38 kHz to 51 kHz, and the compressed pulse shows high resolution with a pulse width of about 1/3 of that using the Chirp wave as transmitting signal. For speed measurement, transmitting signal consisting of two SCT pulses with a time interval of 3.096 ms is employed and moving speed lower than 2 m/s is measured. The measuring results show errors less than 5%. Because the error is proportional to the interval of the dual pulses in the transmitting signal, higher accuracy can be expected by enhancing the interval of the two SCT pulses. These results indicate a possibility of the application of low speed estimation by using ultrasonic pulse-echo method.

METHOD OF SPEED MEASUREMENT

Sensitivity compensated transmitting signal

Neglecting noise, a received signal $S_r(\omega)$ can be expressed as the product of a transmitting signal $S_t(\omega)$ and a transfer function $R(\omega)$ which consists of the sensitivities of transducers $R_S(\omega)$ and the propagating function $R_P(\omega)$.

$$S_r(\omega) = R(\omega)\cdot S_t(\omega) = R_S(\omega)R_P(\omega)\cdot S_t(\omega)\ . \tag{1}$$

Therefore, if we use a transmitting signal with an amplitude characteristic of the spectrum as $|R(\omega)|^{-1}$, a signal with flat spectrum can be received.

In the case that $R(\omega)$ is majorly determined by the sensitivities of transducers, the difference of $R_P(\omega)$ dependent on measuring conditions can be neglected, and thus $R(\omega)$ can be derived from a reference received signal $S_{rc0}(\omega)$ by using a transmitting signal with flat spectrum, e.g., linear FM Chirp wave $S_{tc}(\omega)$.

$$|R(\omega)| = \left|\frac{S_{rc0}(\omega)}{S_{tc}(\omega)}\right| = |S_{rc0}(\omega)| \ . \tag{2}$$

Although the sensitivity compensated signal can be theoritically calculated by $|S_{rc0}(\omega)|^{-1} \cdot S_{tc}(\omega)$, the received signal will be seriously distorted by the noise at the frequency where the value of $S_{rc0}(\omega)$ is small. In this paper, a stabilization factor α is introduced for restraining the divergence caused by noises when the value of $|S_{rc0}(\omega)|$ is small, and thus the SCT signal $S_{ts}(\omega)$ is derived by

$$S_{ts}(\omega) = \frac{|S_{rc0}(\omega)|}{|S_{rc0}(\omega)|^2 + \alpha^2 \cdot |S_{rc0}(\omega)|^2_{\max}} \cdot S_{tc}(\omega) \ . \tag{3}$$

Here, $|S_{rc0}(\omega)|_{\max}$ denotes the maximum value in the amplitude charastics of the spectrum of the reference received signal when using the Chirp wave as transmitting signal. The value of α should be choosen for compensating the spectrum in the band where the value of $|S_{rc0}(\omega)|$ is greater than it while restraining that where the value of $|S_{rc0}(\omega)|$ is less than it. In this paper, considering of the SNR and the effective band width, α=0.05 (-26 dB from the maximum) is employed.

Pulse compression and speed measurement

Normally, the matched filter, which optimizes the SNR by calculating the cross-correlation of a received signal S_r and a reference signal S_0, is employed for pulse compression. Although the transmitting signal is usually used as the reference signal, if the received signal is seriously affected by the sensitivities of the transducers, the effective band width of the cross-correlation result will be narrowed and thus the resolution of the compressed pulse will be lessened.

In our method, signal with flat spectrum is expected to be received by using the SCT signal, and a priorly measured received signal, whose spectrum is also flat, is employed as the reference signal $S_{r0}(\omega)$. The compressed pulse $S_p(\omega)$ is calculated by

$$S_p(\omega) = S^*_{r0}(\omega) \cdot S_r(\omega), \tag{4}$$

where $S_{r0}^*(\omega)$ denotes the complex conjugate of $S_{r0}(\omega)$, and $S_r(\omega)$ is the measured echo signal to be compressed.

For speed measurement, a transmitting signal consisting of two SCT pulses with an interval τ_0 is employed. Considering a transmitter and a receiver are aligned parallel to each other with an interval of d, and a target is moving with speed v in alignment with the center of the axes of the transducers, the speed can be derived by

$$v = \frac{\tau_0 - \tau_r}{\tau_0 + \tau_r} \cdot \cos\left(\tan^{-1}\frac{d}{2R}\right) \cdot c, \tag{5}$$

where τ_r is the interval of dual pulses in received signal reflected from the moving target, c is the sound velocity in the air, and R is the distance between the target and the center of the transducers when the transmitting signal is reaching the target. In various cases of application, R can be estimated by target ranging, or the term $\cos[\tan^{-1}(d/2R)]$ can be neglect if d<<$2R$.

CONDITIONS OF EXPERIMENT

In general application, there is no preknowledge on the propagation function of an ultrasonic pulse reflected from a moving target to be measured. Moreover, normal ultrasonic transducer used in air has a resonant property, which influences the transfer function seriously. Hence, considering only the sensitivities of the transducers, we align two transducers, one as transmitter and one as receiver, facing each other with a distance of 20 cm for measuring the reference received signals, as shown in Fig. 1. In the experiment, two ultrasonic transducers with a 1.5 cm diameter and a 40 kHz resonant peak are employed.

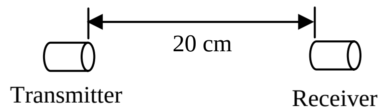

Figure 1. Arrangement of transducers for reference received signal measurement

Figure 2 shows the arrangement of the transducers and the moving target for speed measurement. The transmitter and the receiver are arranged parallel to each other with a 10 cm interval, and a 7 cm × 7 cm square steel plate is employed as the target. The target is carried on a rail-robot system which is speed controllable. The transmitting signal consisting of double pulses is triggered when the target is moving to about 100 cm from the center of the transducers.

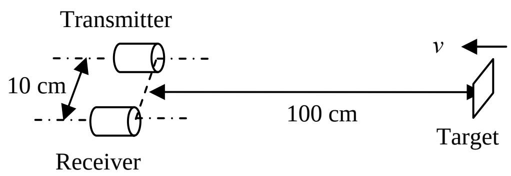

Figure 2. Arrangement of transducers and moving target for speed measurement

In order to study the possibility of measuring comparatively lower speed, speeds between 1 m/s to 2 m/s are measured. In addition, for verifying the effectiveness of the SCT signal, comparison echo pulses using the Chirp wave and the SCT signal as transmitting signal, respectively, are measured and compressed when v=0 m/s.

In all these experiments, the temperature is 26.5°C and thus the sound velocity 347.64 m/s is employed.

RESULTS OF EXPERIMENT

Sensitivity compensated transmitting signal

First, with the arrangement of transducers shown in Fig. 1, the sensitivity response function of the transducers is measured frequency separately by using continuous single-frequency waves as transmitting signals. According to the result, a frequency range of linear FM Chirp wave is determined to be from 35 kHz to 55 kHz. Figure 3 shows the Chirp wave from the signal generator. As shown, the pulse width of the waveform is 2 ms, and the spectrum between about 36 kHz to 53 kHz is nearly flat.

Using the Chirp wave pulse as transmitting signal, a reference received signal of Chirp wave is measured. Figure 4 shows the waveform and its spectrum. As shown, although the spectrum of transmitting signal is approximately flat in

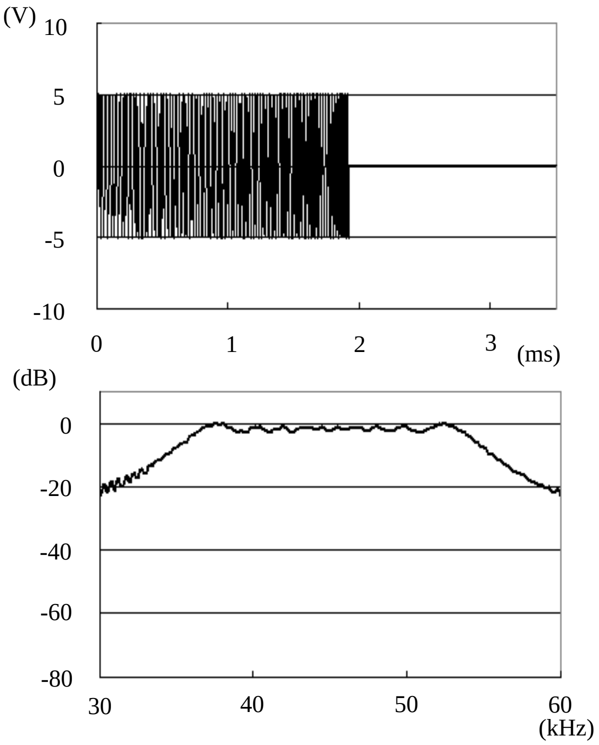

Figure 3. Waveform and spectrum of the Chirp wave

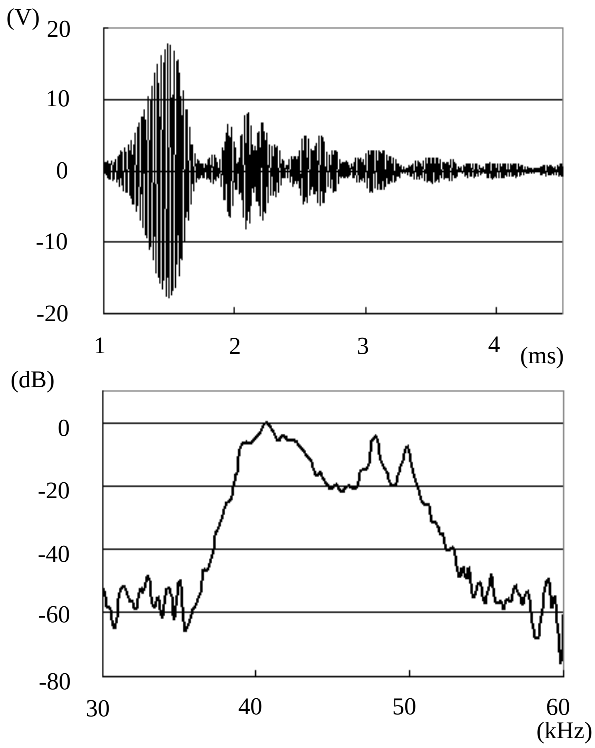

Figure 4. Reference received signal of the Chirp wave

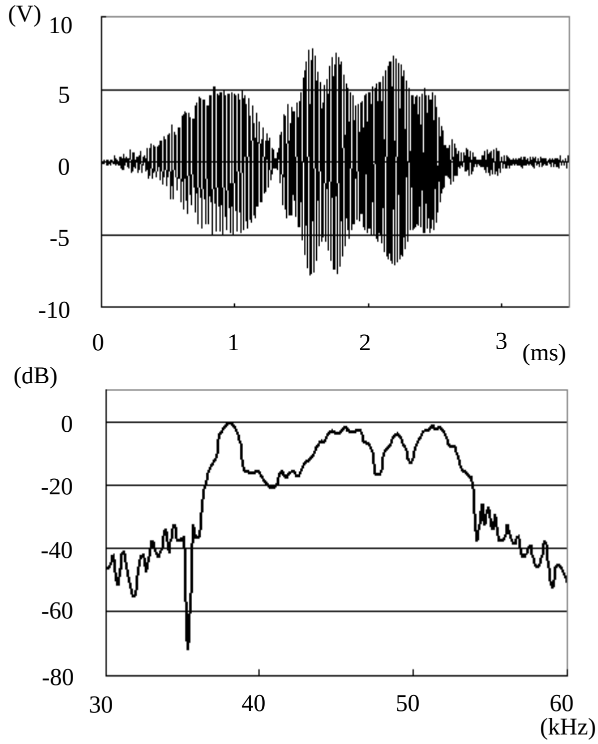

Figure 5. Waveform and spectrum of the SCT signal

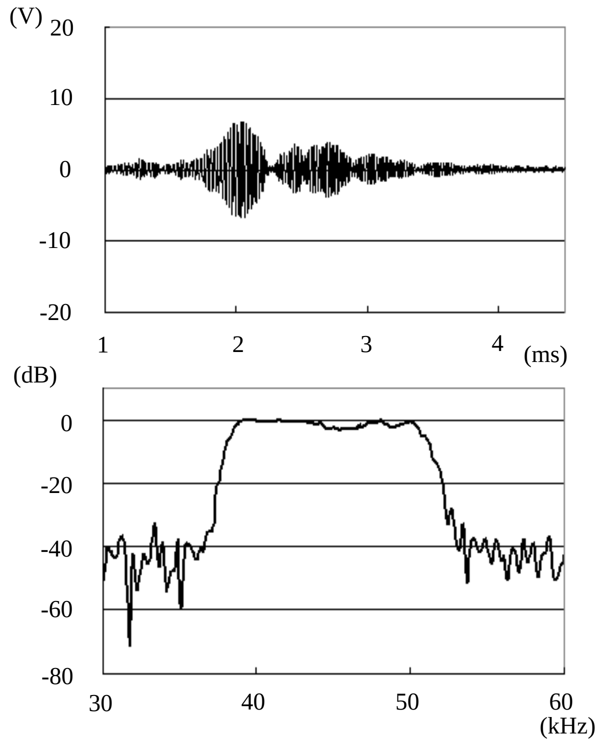

Figure 6. Reference received signal of the SCT signal

the effective band, the spectrum of received signal is markedly influenced by the sensitivities of the transducers.

The SCT signal is then calculated by eq. (1) using the Chirp wave and its reference received signal as $S_{tc}(\omega)$ and $S_{rc0}(\omega)$, respectively. Then the reference received signal of the SCT signal is also measured with the arrangement of transducers shown in Fig. 1. Moreover, for a comparison to the Chirp wave, the amplitude of the SCT signal is normalized by equalizing its envelope area with that of the Chirp wave.

Figures 5 and 6 show the result of the SCT signal and its reference received signal, respectively. As shown in Fig. 6, due to that the inverse filtering compensation reduces the signal amplitude around the resonant frequency of the transducers, the amplitude of the waveform of the received signal is lower than that of the Chirp wave shown in Fig. 4. However, unevenness between -20 dB to 0 dB in the spectrum shown in Fig. 4 is compensated for to be much flatter and broader, that the the spectrum in a broader effective bandwidth between 38 kHz to 51 kHz is almost flat.

Comparison results of pulse compression

Figures 7 and 8 show examples of the pulse compression results of the received echo signals, using the Chirp wave and the SCT signal as transmitting signal, respectively. The echo signals are measured when the distance between the target and the center of the transducers is 100 cm. The amplitudes of the compressed pulses are normalized by their maximum peak. As well, the -6 dB time durations of the compressed pulses are also shown in corresponding figures. Because the received echo signals are similar with those shown in Figs. 4 and 6, they are omitted here.

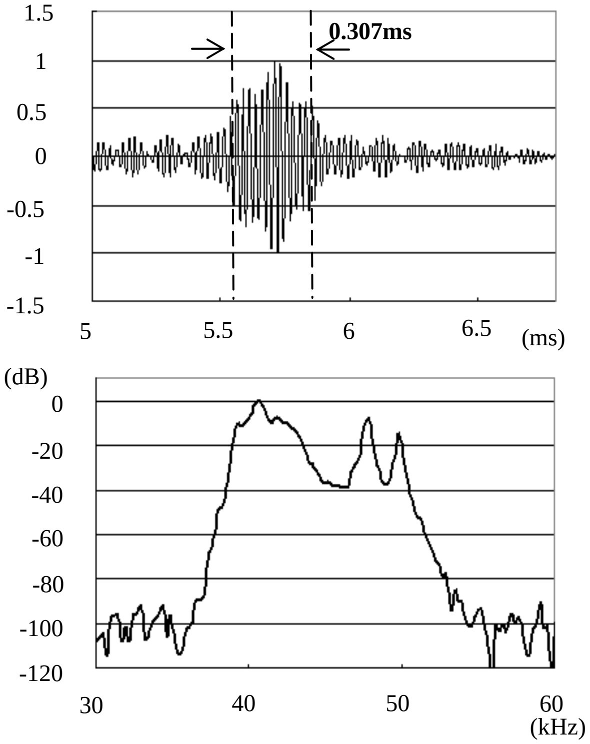

Figure 7. Example of compressed pulse of the Chirp wave

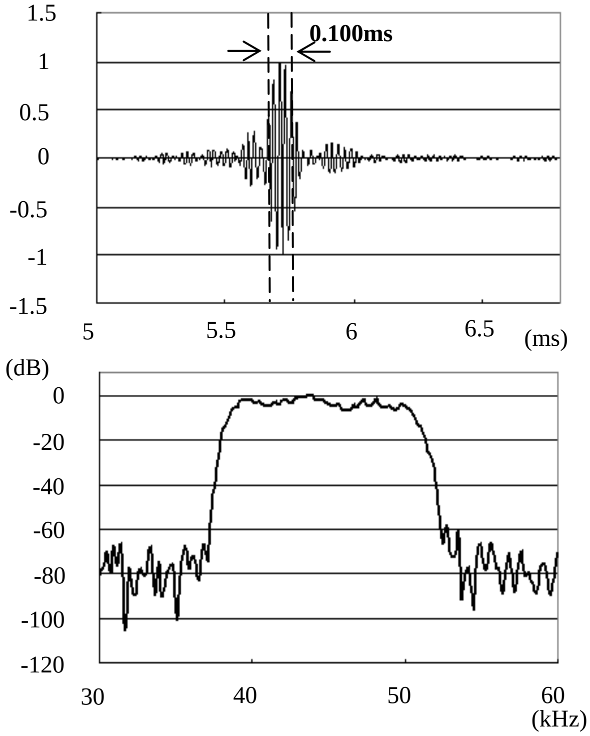

Figure 8. Example of compressed pulse of the SCT signal

It is shown in the results that although the amplitude level of the receiving echo signal of the SCT signal are lower than that of the Chirp wave, the compressed pulse shows a good SNR in Fig. 8. Especially, as shown in the waveforms of the compressed pulses, the -6 dB pulse width corresponding to the SCT signal is shortened to about 1/3 of that corresponding to the Chirp wave. These comparison results verify the effectiveness of the SCT signal on compensating for the unevenness of the spectrum of received signal and thus expanding the effective bandwidth of the received signals efficiently.

Results of speed measurement

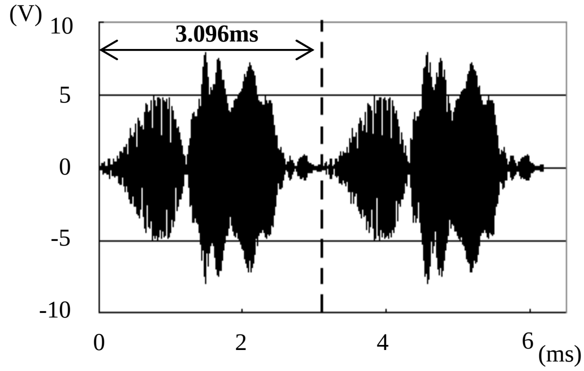

Figure 9. Transmitting signal for speed measurement

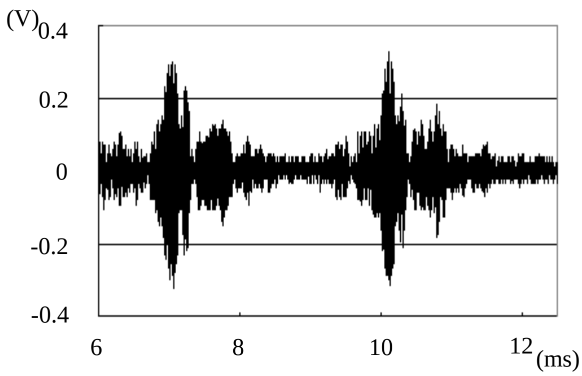

Figure 10. Example of received signal when v=1.7 m/s

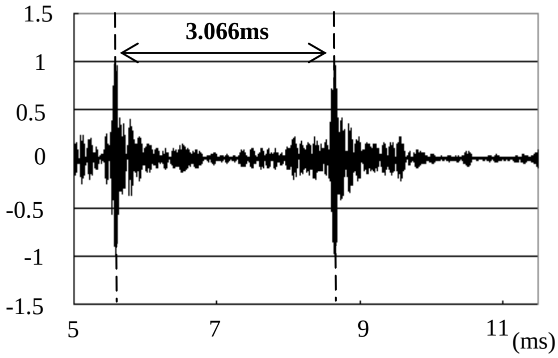

Figure 11. Example of compressed result of the received signal when v=1.7 m/s

Figure 9 shows the waveform of the transmitting signal used for speed measurement. It is composed of two SCT pulse with an interval of 3.096 ms. Figure 10 shows the waveform of an example received echo signal from the moving target when the speed is 1.7 m/s, and Fig. 11 shows the result of pulse compression calculated by the cross-correlation of the echo signal and the reference received signal shown in Fig. 6. From Fig. 11, τ_r=3.066 ms can be derived and the measured speed can be calculated by eq. (5) to be 1.690 m/s. Here, according to the arrangement shown in Fig. 2, R=100 cm and d=10 cm are employed.

Figure 12 shows the results of measured speeds between 1 m/s to 2 m/s with 0.1 m/s step. The results show a good agreement with the speed of controllable rail-robot system, with errors less than 5%. Because the error of speed measurement is considered to be proportional to the interval of the dual SCT pulses used in the transmitting signal, higher accuracy can be expected by enhancing the interval of the two SCT pulses.

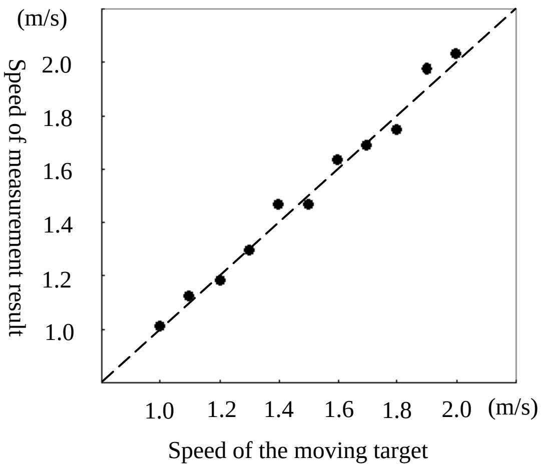

Figure 12. Results of speed measurement

CONCLUSIONS

In order to acquire an ultrasonic received signal with broader bandwidth and flatter spectrum, a sensitivity compensated transmitting signal is proposed. By using the sensitivity compensated transmitting signal and pulse compression, the received signal reflected from target has broader bandwidth and flatter amplitude characteristic, and the compressed pulse has a narrower pulse width which enhances the resolution.

Moreover, by using a transmitting signal consisting of two sensitivity compensated pulses, comparatively low speed of moving target is measured. The results are good with errors less than 5% which can be expected to be lessened furthermore by enhancing the interval of the two sensitivity compensated pulses. These results indicate a possibility of the application of low speed estimation by using ultrasonic pulse-echo method.

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