# Airborne Ultrasonic Position and Velocity Measurement Using Two Cycles of Linear-Period-Modulated Signal

Shinya Saito[1], Minoru Kuribayashi Kurosawa[1], Yuichiro Orino[1], and Shinnosuke Hirata[2]

[1] Department of Information Processing, Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan
saitou.s.aa@m.titech.ac.jp, mkur@ip.titech.ac.jp, orino.y.aa@m.titech.ac.jp
[2] The University of Electro-Communications, Tokyo, Japan
hirata@mce.uec.ac.jp

**Abstract.** Real-time position and velocity measurement of a moving object with high accuracy and resolution using an airborne ultrasonic wave is difficult due to the influence of the Doppler effect or the limit of the calculation cost of signal processing. The calculation cost had been reduced by single-bit processing and pulse compression using two cycles of linear-period-modulated (LPM) signal. In this paper, accuracy of the ultrasonic two-dimensional position and velocity vector measurement of the proposed method using two microphones is evaluated by experiments.

**Keywords:** ultrasonic position and velocity measurement, pulse compression, linear-period-modulation, single-bit signal.

## 1 Introduction

Acoustic sensing systems are used in many industrial applications due to advantages of acoustic sensors, their low-purchase cost, small size, and simple hardware. Method of airborne ultrasonic measurement are widely researched [4][5]. 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 [8]. Pulse compression has been introduced in the pulse-echo method for improvement of the signal-to-noise ratio (SNR) of the reflected echo and distance resolution [7].

A linear-frequency-modulated (LFM) signal is used in the pulse-echo method. The frequency of LFM signal linearly sweeps with time. A received signal is correlated with a reference signal which is the transmitted LFM signal. The TOF of the transmitted signal is estimated by the maximum peak in the cross-correlation function of received signal and reference signal. The signal processing for cross-correlation consists of huge iterations of multiplications and accumulations. Therefore, real-time ultrasonic measurement is difficult because of the high cost in digital signal process.

R. Groß et al. (Eds.): TAROS 2011, LNAI 6856, pp. 46–53, 2011.

So a signal process method using a delta-sigma modulated single-bit digital signal has been proposed to reduce the calculation cost of cross-correlation. The proposed signal processing consists of a recursive cross-correlation by single-bit signals of and smoothing operation by a moving average filter. The calculation cost of cross correlation is reduced by the recursive cross-correlation operation of single-bit signals [2].

In the case of a moving object, the reflected signal is modulated due to the Doppler effect caused by the object motion. The linear shift of the signal period means the hyperbolic shift of the frequency. Therefore, a Doppler-shift LFM signal cannot be correlated with a reference LFM signal. So pulse compression using a linear-period-modulated (LPM) signal has been introduced for ultrasonic measurement of a moving object [6][1]. The signal period of the LPM signal linearly sweeps with time. Thus, a Doppler-shift LPM signal can be correlated with a reference LPM signal.

However, the cross-correlation function of the Doppler-shift LPM signal and a reference LPM signal is also modulated due to Doppler effect. The method of typical Doppler-shift compensation is high cost using the envelop but Doppler-shift compensation is required. A low-calculation-cost method of ultrasonic measurement by pulse compression using two cycles of LPM signal and Doppler-shift compensation has been already proposed [3].

Ultrasonic distance and velocity measurement have been already achieved by using one microphone[3]. In this paper, method of two-dimensional position and velocity vector measurement are considered by using two microphones, and accuracy of the two-dimensional position and velocity vector measurement are evaluated by experiments.

## 2 Cross Correlation by Single-Bit Processing

The proposed method of ultrasonic distance and velocity measurement by pulse compression using two cycles of LPM signal is illustrated in Fig. 1 [2]. In the proposed method, two cycles of LPM signal are transmitted by a loudspeaker. The received signal of one 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 of N samples by a digital comparator.

The cross-correlation function $c_1(t)$ of the received signal $x_1(t)$ and the reference signal $h_1(i)$ is expressed as

$$c_1(t) = \sum_{i=0}^{N-1} h_1(N-i) \cdot x_1(t-i) \tag{1}$$

The calculation of the cross-correlation operation of Eq. (1)requires huge numbers N of multiplica-tions and accumulations of single-bit samples.

The difference of the cross-correlation function, $C_1(t)-C_1(t-1)$, is expressed as

$$c_1(t) - c_1(t-1) = h_1(N) \cdot x_1(t) - h_1(1) \cdot x_1(t-N)$$

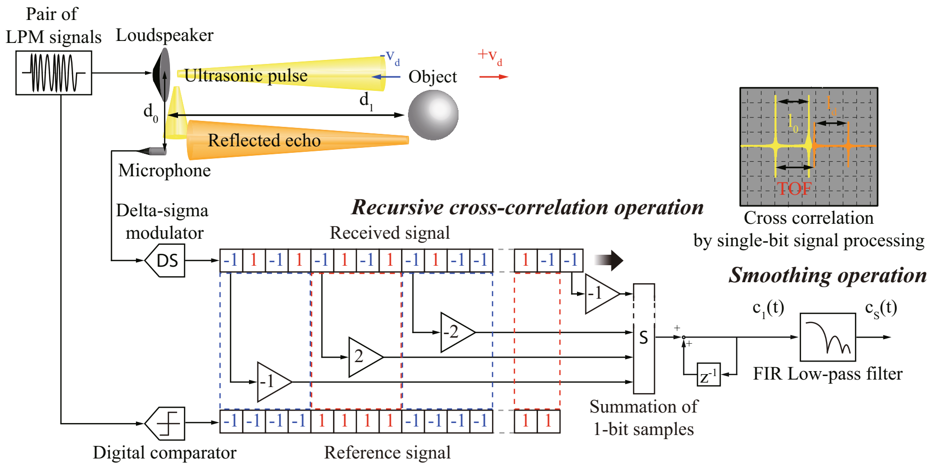


**Fig. 1.** The singal processing of ultrasonic position and velocity measurement by pulse compression using two cycles of LPM signal

$$+\sum_{i=1}^{N-1}\{h_1(N-i)-h_1(N-i+1)\}\cdot x_1(t-i) \tag{2}$$

The values of $h_1(1)$ and $h_1(N)$ are 1 and -1 respectively. Furthermore, $h_1(i)$ has several hundreded zero-cross points $Z_i$. The values of $h_1(N-1)-h_1(N-i+1)$ are expressed as

$$h_1\left(N-i\right)-h_1\left(N-i-1\right)=\begin{cases} 2, & \cdots N-i=Z_{2m-1}. \\ -2, & \cdots \quad N-i=Z_{2m}. \\ 0, & \cdots \quad N-i\neq Z_i. \end{cases} \tag{3}$$

where m is a natural number. The calculation of the recursive cross-correlation operation, which is performed by integrating the difference of the cross-correlation function, is expressed as

$$\begin{aligned} c_1(t) = c_1(t-1) - x_1(t-N) + 2\cdot x_1(t-N+Z_1) \\ -2\cdot x_1(t-N+Z_2) + \cdots - x_1(t) \end{aligned} \tag{4}$$

The calculation cost of the recursive cross-correlation operation is integration and summations of single-bit samples. The number of summations $Z_i$+2 only depends on the number of zero-cross points in the transmitted LPM signal.

## 3 The Method of Position and Velocity Measurement

### 3.1 Two-Dimensional Position Measurement

The TOF of an echo is estimated from the cross-correlation function. The arrangement of microphones, the loudspeaker, and the object is shown in Fig. 2. In

Fig. 2, $d$ is a distance from the loudspeaker to the object, $\theta$ is an angle between the loudspeaker and the object, and $L$ is a distance from the loudspeaker to microphones. The TOF of the microphone-1 and the microphone-2 have usually different values of $TOF_1$ and $TOF_2$ respectively. When $d$ is much larger than $2L$, $\theta$ is

$$\theta = sin^{-1}\frac{(TOF_1 - TOF_2)c}{2L} \tag{5}$$

where $c$ is the propagation velocity of an ultrasonic wave. Using the angle $\theta$, the distance $d$ is simply derivated by geometric calculation.

### 3.2 Two-Dimensional Velocity Vector Measurement

The method of the velocity vector measurement is illustrated in Fig. 3 and Fig. 4. In this method, the doppler velocity can be estimated from the signal length of the transmitted signal and the echo. The signal length difference is in proportion to the velocity of the object as shown in Fig. 3. The signal length is detected from the interval of the cross-correlation function peaks by two cycles LPM signals.

The measured velocities are the vector components of the ultrasonic propagation direction, which is $v_1$ and $v_2$ in Fig. 4, in the proposed method of ultrasonic measurement by pulse compression using two cycles of LPM signal. The measured velocity $v_1$ is a component of the object velocity $v$; the direction of $v_1$ is estimated from the geometrical relation between the distance $d$, the angle $\theta$ and the space $L$. Namely, from the measurement using the microphone-1, one velocity component of $v$ is obtained correspondence to the direction of $v_1$. Similarly,

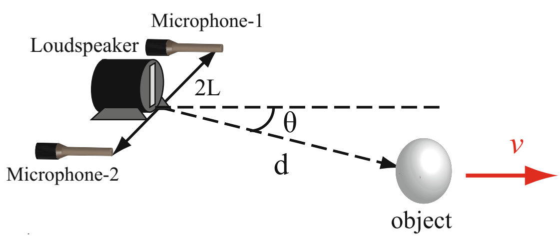


**Fig. 2.** The method of ultrasonic position measurement

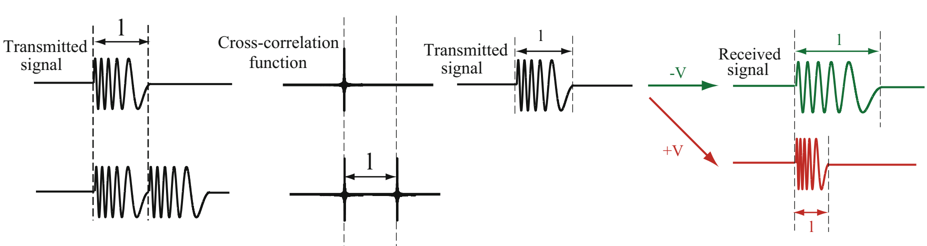


**Fig. 3.** The change of the signal length

another velocity component of the object velocity $v$, namely $v_2$, is acquired by using the microphone-2. Now, taken the vectors which is normal to the $v_1$ and $v_2$ respectively, the vectors intersect at one point. The velocity $v$ is estimated from intersection point drawn in Fig. 4.

## 4 Experiment

### 4.1 Experimental Setup

The experimental setup for the ultrasonic two-dimensional position and velocity vector measurement is illustrated in Fig. 5. In the experiment, the period of the transmitted LPM signal linearly swept from 20 $\mu$s to 50 $\mu$s. The length of the transmitted LPM signal was 3.274 ms, the driving voltage of the loudspeaker was $2V_{p-p}$. The LPM signal was generated from the function generator and amplified by an amplifier. Two cycles of the LPM signal were transmitted by the loudspeaker, and the echo from the object was detected by two microphones. The distance from the loudspeaker to the microphones were 0.09 m. The propagation velocity of an ultrasonic wave in the air was approximately 348.8 m/s at 27.0°C. The received signals by the microphones were converted into the single-bit delta-sigma modulated signals. The sampling frequency of the delta-sigma modulator was 12.5 MHz.

The received signals were correlated with the single reference signal using MATLAB on the computer. The reference signal was simply converted into a single-bit signal by the digital comparator. The cross-correlation function of the received signal and the reference signal was obtained from a recursive cross-correlation operation of single-bit signals and a smoothing operation by a weighted moving average filter. The length of the filter was 141 taps.

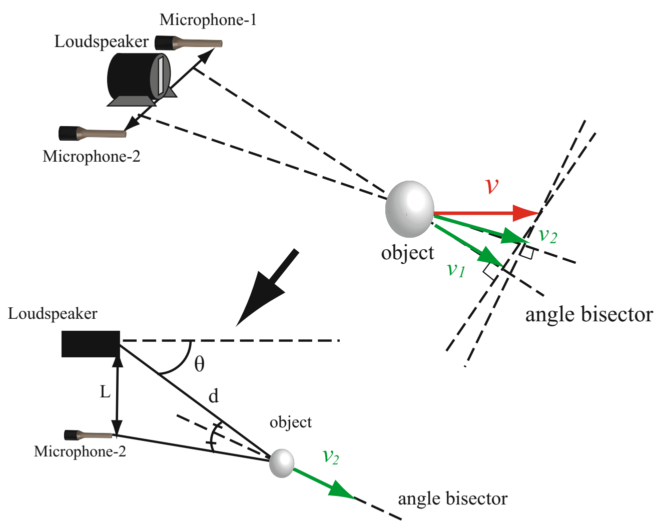


**Fig. 4.** The method of ultrasonic velocity measurement

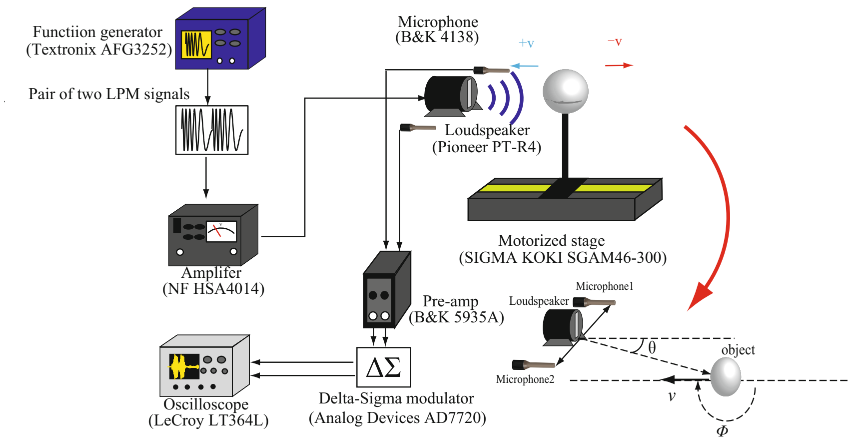


**Fig. 5.** Experimental setup of ultrasonic position and velocity measurement

Accuracy of the position and velocity measurement was evaluated by experiments. The object was a plastic ball whose diameter was 17 cm. The object distance $d$ was 1.05 m and the angle $\theta$ was 20° to the object when two cycles of the LPM signal was transmitted. The velocity of the object was 0.4 m/s, the direction of movement was normal to a straight line that links the microphones and the loudspeaker, $\Phi = 180°$ in Fig. 5. The measurement was executed 150 times.

### 4.2 Experimental Result

The cross-correlation function was obtained by experiments as shown in Fig. 6. The first two peaks of cross-correlation function were caused by the waves which the microphone received from the loudspeaker directly. The second two peaks of cross-correlation function were caused by the echo from the object. The peak of the cross-correlation function was detected by limiting the time range of cross-correlation function and calculating the maximum point in the limited time range.

The probability distribution of the distance and the angle are illustrated in Fig. 7. Average and standard deviation of the distance and angle were 1.066 m and 73.8 $\mu$m, 19.5° and 0.09° respectively. The average of distance and angle were a little different from the setup value, but it is inevitable that errors are observed about 2 to 3 cm and 1 to 2° when the object's position was set. Given that, it can be said that high accuracy of the distance and angle by the proposed method is demonstrated by experiments of the ultrasonic two-dimensional position measurement.

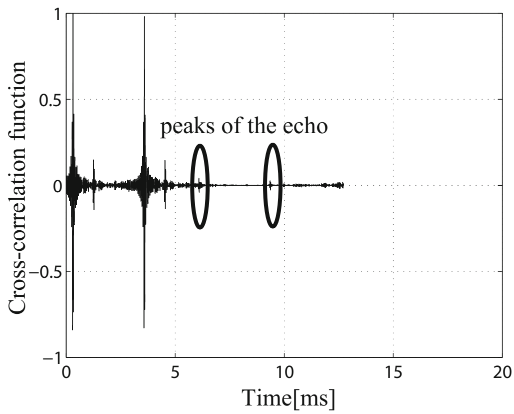


**Fig. 6.** Cross-correlation function

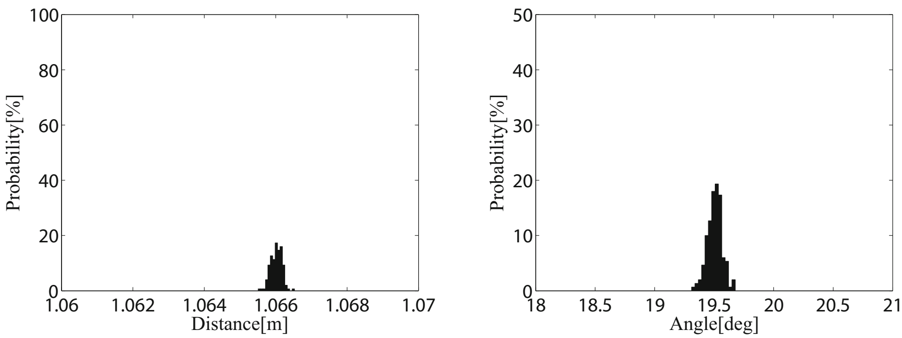


**Fig. 7.** The probablity distributions of the position, distance(left) and angle(right)

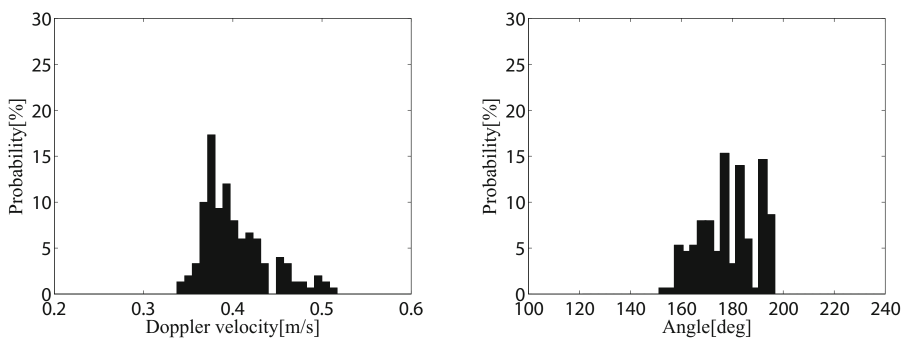


**Fig. 8.** The probablity distributions of the velocity(left) and direction angle(right)

The probability distribution of velocity is also illustrated in Fig. 8. Average and standard deviation of the velocity and the direction angle of movement were 0.403 m/s and 0.038 m/s, 178.3° and 10.9° respectively. Average of the velocity and direction of movement were near to setup value, but standard deviations of the velocity and the angle were a little large. The approximate value of the object's velocity vector can be estimated, but the measuring accuracy needs to be improved slightly.

## 5 Conclusion

Accuracy of airborne ultrasonic two-dimensional position and velocity vector measurement using two microphones with two cycles of LPM signal was examined by experiments. Experiments were executed using a recursive cross-correlation by single-bit signals and a low-calculation-cost method of Doppler-shift compensation. High accuracy regarding the ultrasonic position measurement was obtained. On the other hand, there was room for improvement regarding velocity vector measurement but the approximate value of the object's velocity can be estimated. Now a recursive cross-correlation is being implemented in FPGA because ultrasonic two-dimensional position and velocity measurement was not real-time in these experiments. For the future work, multi moving object in the area will be considered.

## References

1. Altes, R.A., Skinner, D.P.: Sonar-velocity resolution with a linear-period-modulated pulse. J. Acoust. Soc. Am. 61(4), 1019–1030 (1977)
2. Hirata, S., Kurosawa, M.K., Katagiri, T.: Cross-correlation by single-bit signal processing for ultrasonic distance measurement. IEICE Trans. Fundam. E91(A), 1031–1037 (2008)
3. Hirata, S., Kurosawa, M.K., Katagiri, T.: Ultrasonic distance and velocity measurement by low-calculation-cost doppler-shift compensation and high-resolution doppler velocity estimation with wide measurement range. Acoustical Science and Technology 30(3), 220–223 (2009)
4. Jorg, K.W., Berg, M.: Sophisticated mobile robot sonar sensing with pseudo-random codes. Robotics and Autonomous Systems 25(3), 241–251 (1998)
5. Klahold, J., Rautenberg, J., Ruckert, U.: Continuous sonar sensing for mobile mini-robots. In: Proc. the 2002 IEEE International Conference on Robotics and Automation, vol. 1, pp. 323–328 (2002)
6. Kroszczynski, J.J.: Pulse compression by means of linear-period modulation. Proc. of the IEEE 57(7), 1260–1266 (1969)
7. Marioli, D., Narduzzi, C., Offelli, C., Petri, D., Sardini, E., Taroni, A.: Digital time-of-flight measurement for ultrasonic sensors. IEEE Trans. Instrumentation and Measurement 41(1), 93–97 (1992)
8. Marioli, D., Sardini, E., Taroni, A.: Ultrasonic distance measurement for linear and angular position control. IEEE Trans. Instrumentation and Measurement 37(4), 578–581 (1988)