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Two-Dimensional Airborne Position and Velocity Measurements Using a Pair of Linear-Period-Modulated Ultrasonic Waves

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Summary

This paper proposes an idea for position and velocity measurements for a moving object with the echolocation technique under the ultrasonic system. The moving-object location is based on the time-of-flight (TOF). Cross correlation, low-calculation-cost Doppler-shift compensation, plays an important role in the TOF determination. The over-sampling cross-correlation function is obtained from single-bit signal processing. The velocity of the moving object is determined from the peak interval and peak form in the cross-correlation function. Linear-period-modulated (LPM) ultrasonic waves are employed to support the influence of the Doppler effect. In this paper, the ultrasonic two-dimensional position and velocity vector measurement exploits two microphones. The validity of this paper is experimentally evaluated.

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1. Introduction

Acoustic sensing systems are useful in many industrial applications due to advantages of acoustic sensors, namely, their low-purchase cost, small-system size, and simple hardware. Especially with respect to ultrasonic measurement, this type of system has been widely researched in a variety of applications [1–5]. For the distance measurements that use ultrasonic waves, these systems can be applied because the structures easily reflect them. The pulse-echo method is one for the typical methods of ultrasonic distance measurement [6,7]. In general, this technique is dependent on the determination of the TOF of an echo that is reflected from an object [8–10]. Moreover, pulse compression has been proposed in the pulse-echo method for signal-to-noise ratio (SNR) improvement of the reflected echo and distance resolution [11].

A linear-frequency-modulated (LFM) signal, which indicates a change in the instantaneous frequency with linear time, is based on of pulse compression. This approach has a significant amount of potential in sonar, radar, and ultrasonic applications, for example. When a received signal is correlated with a reference signal, which is the transmitted LFM signal, the TOF can be computed by the maximum peak in the cross-correlation function of the received and reference signals. To achieve a high resolution in the signal, a delta-sigma modulator, which gives a single-bit stream analog-to-digital circuit, can be used in a simple manner and has a relatively high-tolerance in its analog components [12]. However, the single-bit signal processing for cross-correlation consists of very large iterations of multiplications and summations. In addition, real-time ultrasonic measurement is difficult because of the high cost of the digital signal process. Therefore, a signal processing method that use a delta-sigma modulated single-bit digital signal has been presented to decrease the computation cost of the cross correlation. The proposed signal processing consists of a recursive cross-correlation of single-bit signals and a smoothing operation by a moving average filter. The calculation cost of the cross correlation is reduced by the recursive cross-correlation operation of the single-bit signals [13,14].

In the case of a moving object, the reflected signal is modulated due to the Doppler effect, which is caused by the objects motion. The linear shift of the signal period directly affects the non-linear shift of the frequency. Indeed, a Doppler-shift LFM echo cannot be perfectly correlated

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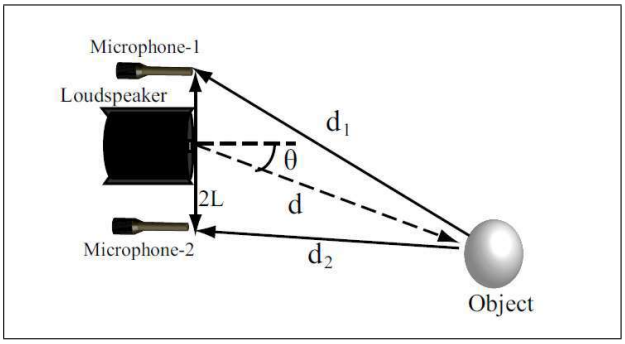

Figure 1. The method of ultrasonic position measurement.

with a reference LFM signal. To overcome this problem, pulse compression that uses a linear-period-modulated (LPM) signal has been introduced for ultrasonic measurement of a Doppler-shift effect [15,16]. The signal period of the LPM signal sweeps linearly with time. Thus, a Doppler-shift LPM signal can be correlated with a reference LPM signal as well. However, the cross-correlation function by the Doppler-shift LPM signal and a reference LPM signal is also modulated due to the Doppler effect. The method of typical Doppler-shift compensation using the envelop peak signal has high-cost-time consumption. To support real-time applications, a low-calculation-cost method of ultrasonic measurement by pulse compression using two cycles of LPM signal and Doppler-shift TOF compensation has been already proposed in [17]. In this technique, the Doppler velocity can be computed from the peak interval and peak form in the modulated cross-correlation function by numerical calculation alone. Then, TOF due to Doppler-shift compensation has been improved to be more accuracy [18].

Ultrasonic distance measurement based on single-bit processing has been already achieved by using one microphone [19]. In this paper, a method of two-dimensional position and velocity vector measurements is considered by using two microphones for supporting a real-time application by only the time domain of single-bit signal processing. However, a limitation of the proposed method involving with acoustics requires a intensive reflected echo to return from an object. This system is blinded if a target for localization is a sound-absorption material. To confirm the validity, the accuracy of the two-dimensional position and velocity measurement are evaluated by experiments when a mirror surface is set as a target.

2. The method of two-dimentional position and velocity measurements

2.1. Two dimentional position measurement

The over-sampling signal processing of two-dimensional ultrasonic position and velocity measurements by pulse compression using a pair of LPM signals is exploited. LPM signals is directly transmitted with a loudspeaker. A receiving echo that is reflected from a moving object is obtained with two microphones. The echo is converted into single-bit data by a delta-sigma modulator. On the other hand, the reference single LPM signal is changed into a single-bit signal by a digital comparator. The cross correlation between the received signal and the reference signal is obtained by single-bit signal processing. The TOF of the received LPM signal is typically estimated from the maximum peak time in the cross-correlation function. The arrangement of the microphones, loudspeaker, and object is depicted in Figure 1. Here, θ is position angle between the loudspeaker and object, and L is a distance from the loudspeaker to the microphones. The TOFs of the microphone-1 and microphone-2 usually have different values of TOF_1 and TOF_2, respectively. When considering the far-field assumption [20], d is located far from a pair of microphones such that the wave front reflected by the object arrives at the microphones with an equal direction of propagation. Thus, the propagating field of the echo that is incident on the microphones is considered to be parallel to one another. This assumption can be realized by making d much larger than a distance $2L$ between microphone-1 and microphone-2, and the position angle θ is

$$\theta = \sin^{-1} \frac{(\mathrm{TOF}_1 - \mathrm{TOF}_2)c}{2L}, \tag{1}$$

where c is the propagation velocity of an ultrasonic wave. Using the position angle θ, the distance d is simply derived by the geometric calculation. However, before inserting TOF_1 and TOF_2 into (1), the TOF of the obtained LPM signal is typically computed from the maximum peak time, which is the same as the envelopes peak time in the cross-correlation function. When considering a moving object, the maximum peak time might not be the same as the envelopes peak time in the cross-correlation function. Accordingly, the envelopes peak time is required in a Doppler-shift compensation. The difference in the TOF due to the Doppler velocity can be illustrated in (2), where v_d is the Doppler velocity, T_0 is the initial period of the LPM, ΔT is the chirp width of the LPM, and l is the length of LPM. Therefore, the Doppler-shift compensation of the TOF is manipulated in [17].

$$\Delta\mathrm{TOF} = \frac{v_d}{c + v_d} \cdot \frac{T_0}{\Delta T} l. \tag{2}$$

Considering Figure 1 again, if d is not much larger than a distance $2 \cdot L$ between microphone-1 and microphone-2, the θ can be examined as

$$\theta = \frac{\delta_d}{L} \cdot \left(1 + \frac{(L^2 - \delta^2)}{8d^2}\right) \cdot \frac{360^\circ}{2\pi}, \tag{3}$$

where $\delta_d = d_1 - d_2$. A triangle between the object, the speaker and microphone-1 is

$$d_1^2 = d^2 + L^2 - 2dL\cos(90^0 + \theta), \tag{4}$$

and $d + d_1 = \mathrm{TOF}_1 c$. We can rewrite Equation (4) as

$$d_1 = \frac{\mathrm{TOF}_1^2 c^2 + L^2 + 2\mathrm{TOF}_1 cL\sin\theta}{2\mathrm{TOF}_1 c + 2L\sin\theta}. \tag{5}$$

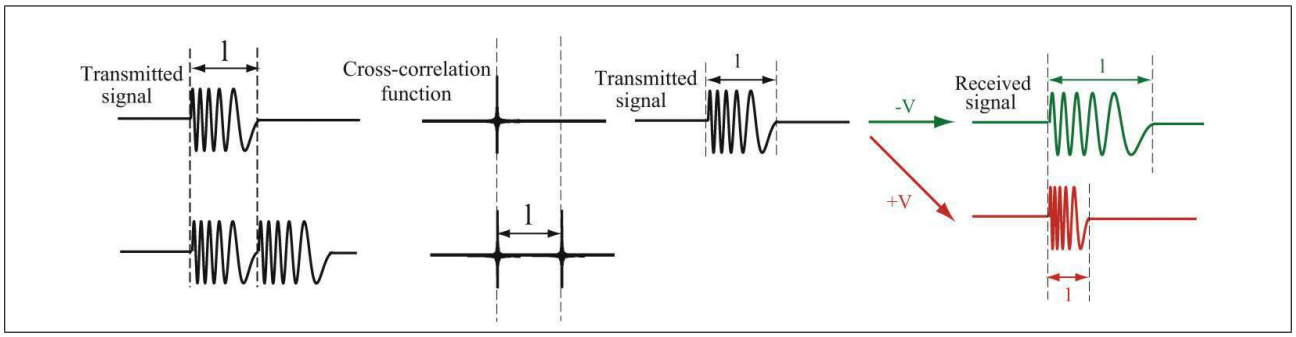

Figure 2. The change in the signal length.

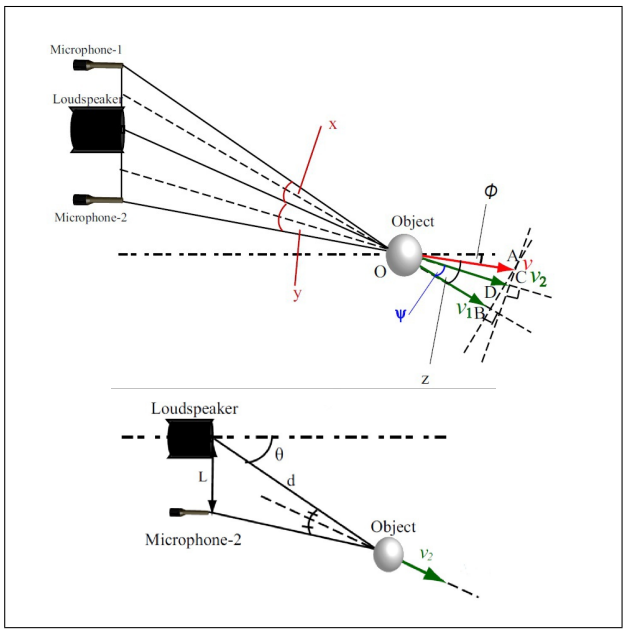

Figure 3. The method of two dimensional vector measurement.

Similarly, in the case of d_2, it can be expressed as

$$d_2 = \frac{\mathrm{TOF}_2^2 c^2 + L^2 + 2\mathrm{TOF}_2 cL\sin\theta}{2\mathrm{TOF}_2 c + 2L\sin\theta}. \tag{6}$$

According to the Trigonometry law in Figure 1, we can create a formula, that connects, in Equation (3).

$$d^2 + 2dL\sin\theta + (L^2 - d_1^2) = 0. \tag{7}$$

Finally, the distance measurement between the object and speaker is

$$d = -L\sin\theta + \sqrt{(L\sin\theta)^2 - (L^2 - d_1^2)}. \tag{8}$$

2.2. Two dimensional velocity vector measurement

The method of the velocity measurement is illustrated in Figure 2 and Figure 3. In this case, the velocity can be estimated from the signal length of the echo, which is reflected from the target. The signal length difference is in proportion to the velocity of the object as shown in Figure 2 . The signal length is detected from the interval of cross correlation peaks by two cycles LPM signals. The velocities measured by pulse compression of the two-cycle LPM signals are the vector components, v_1 and v_2, in Figure 3, of the ultrasonic propagation direction. The measured velocity v_1 is a component of the object velocity v; and the direction of v_1 is estimated from the geometrical relation between the distance d, position angle θ, and space L. In general, from the measurement using microphone-1, one velocity component of v is obtained that corresponds to the direction of v_1. Similarly, another velocity component, namely v_2, is acquired by using microphone-2. Next, taking the vectors that are normal to v_1 and v_2 respectively, the vectors intersect at one point. The velocity v is estimated from the intersection point drawn in Figure 3. The direction angle can be computed by , d_1 and d_2 as the distance between microphones 1, and 2 and the object. In Figure 3, we can obtain $OA^2 = OB^2 + AB^2$ from the Pythagorean theory. Then,

$$OA = \sqrt{OB^2 + \left(\frac{OB}{\tan\psi} - \frac{OC}{\sin\psi}\right)^2}. \tag{9}$$

In other words, for $|\vec{v}_2| > |\vec{v}_1|$,

$$|\vec{v}| = \sqrt{|\vec{v}_1|^2 + \left(\frac{|\vec{v}_1|}{\tan\psi} - \frac{|\vec{v}_2|}{\sin\psi}\right)^2}. \tag{10}$$

When $|\vec{v}_1| > |\vec{v}_2|$,

$$|\vec{v}| = \sqrt{|\vec{v}_2|^2 + \left(\frac{|\vec{v}_2|}{\tan\psi} - \frac{|\vec{v}_1|}{\sin\psi}\right)^2}. \tag{11}$$

The angle $\angle z$ between $|\vec{v}|$ and $|\vec{v}_1|$ is identified by

$$z = \cos^{-1}\frac{|\vec{v}|}{|\vec{v}_1|}. \tag{12}$$

The direction angle ϕ can be considered by the sign of $\vec{v}_1, \vec{v}_2$ and the magnitude of these vectors. In this paper, we set $\phi = 0°$ when the object moves away perpendicularly from the loudspeaker and microphone, and we assume that $\phi < 0°$ for counterclockwise, and $\phi > 0°$ for clockwise.
***Case*1** : When $|\vec{v}_1|, |\vec{v}_2| > 0$ and $|\vec{v}_1| > |\vec{v}_2|$,
$\phi = \frac{x}{2} + \theta + z + 180°$.

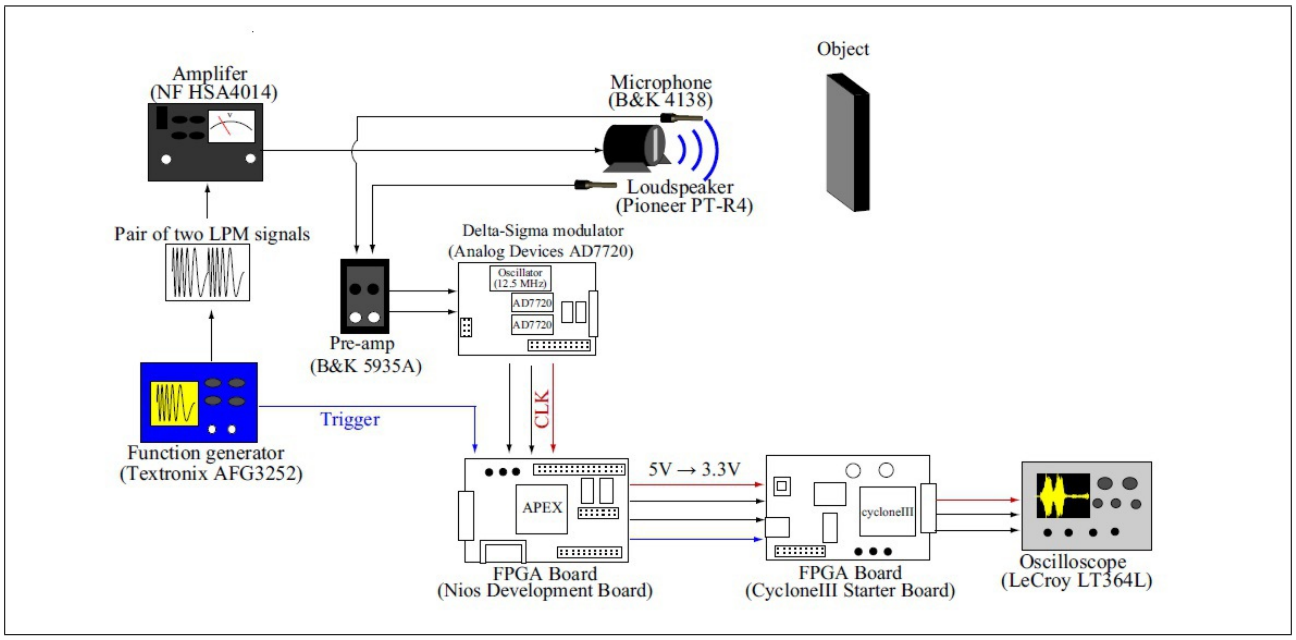

Figure 4. The experimental setup.

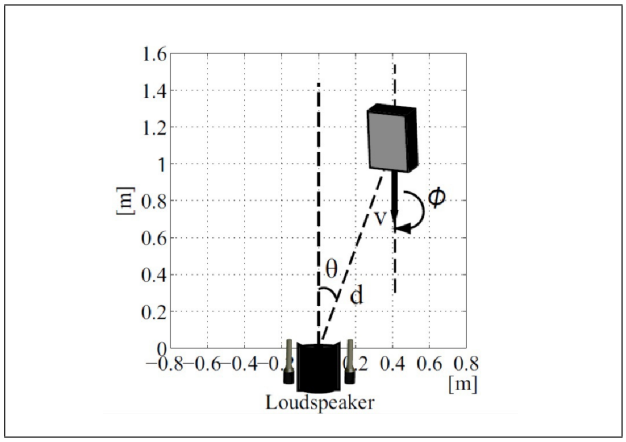

Figure 5. Distance $d = 1.2$ m, direction angle $\phi = 180°$, angle $\theta = 20°$, and changing the velocity of the target to $v = 0.1,0.2,0.3,0.4$ m/s.

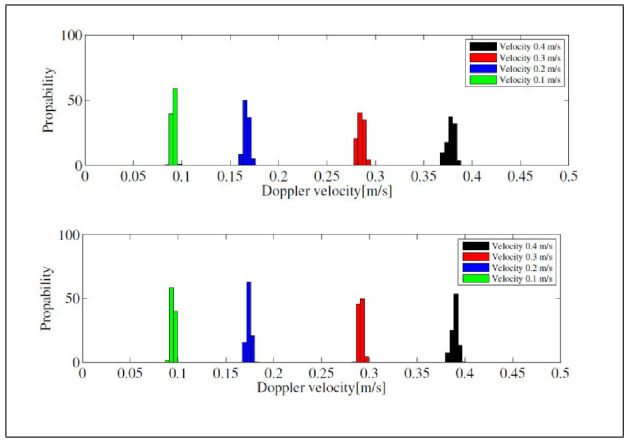

Figure 6. The velocity measurement at the left and right microphones on the top and bottom pictures, respectively, at $d = 1.2$ m, $\phi = 180°$ and $\theta = 20°$ when changing the object velocity to v= 0.1, 0.2, 0.3, 0.4 m/s.

***Case*2** : When $|\vec{v}_1|, |\vec{v}_2| > 0$ and $|\vec{v}_1| < |\vec{v}_2|$,
$\phi = \frac{x}{2} + \theta - z + 180°$.
***Case*3** : When $|\vec{v}_1|, |\vec{v}_2| < 0$ and $|\vec{v}_1| > |\vec{v}_2|$,
$\phi = \frac{x}{2} + \theta + z$.
***Case*4** : When $|\vec{v}_1|, |\vec{v}_2| < 0$ and $|\vec{v}_1| < |\vec{v}_2|$,
$\phi = \frac{x}{2} + \theta - z$.

3. Evaluation of the proposed method by experiment

3.1. Experimental setup

The experimental setup for the ultrasonic two-dimensional position and velocity is pictured in Figure 4. In the experiment, the period of the transmitted LPM signal is linearly swept from 20 μs to 50 μs. The length of the transmitted LPM signal was 3.274 ms, and the driving voltage of the loudspeaker was 2 V_{p-p}. The LPM signal was generated from the function generator and enlarged by 20 times with an amplifier. Two cycles of the LPM signal were transmitted by the loudspeaker, and the echo from the object was detected by the two microphones. The distance from the loudspeaker to the microphone was 0.11 m. The propagation velocity of an ultrasonic wave in the air was approximately 348.8 m/s at 27°C. The signals received by the microphones were converted into the single-bit delta-sigma modulated signals by the 7th-order delta-sigma modulator. The sampling frequency of the 7th-delta-sigma modulator was 12.5 MHz. The referent signal is generated using MATLAB on the computer. The cross-correlation function of the received and referent signals was obtained from a recursive cross-correlation of single-bit signals and a smoothing operation by weighted moving average filter,

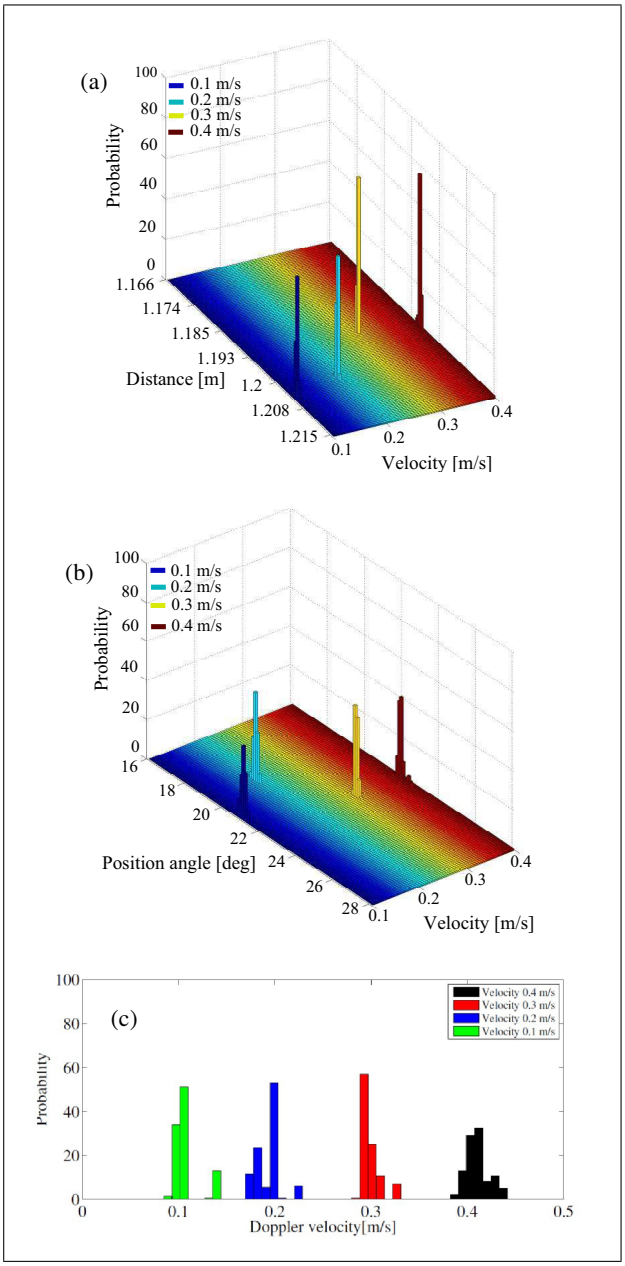

Figure 7. Distributions of changing the velocity to 0.1, 0.2, 0.3, and 0.4 m/s at distance = 1.2 m and position angle = 20° (a) distance distributions (b) position - angle distributions (c) velocity distributions.

the length of which was 141 taps. A cross correlation was designed and embedded on the FPGA boards. The accuracy of the position and the velocity measurement was evaluated by the experiment results. The object was an aluminum flat plate, whose width, length, and thickness were 250, 170, and 40 mm.

3.2. Experimental results

3.2.1. Experimental results of the object position and velocity measurement obtained by varying the speed of the target

In this experiment, the object position is demonstrated by a distance d between a sound source and an object, and

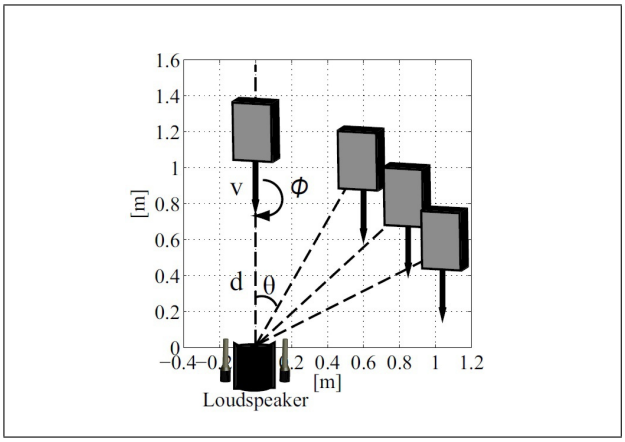

Figure 8. Distance $d = 1.2$ m, velocity $v = 0.4$ m/s direction angle $\phi = 180°$ of the target when changing the position angle θ of the target to 0°, 30°, 45°, and 60°.

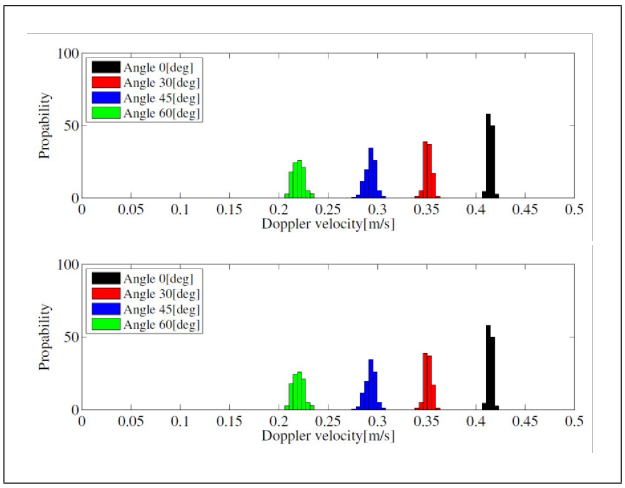

Figure 9. The velocity measurement (a) left microphone (b) right microphones at $d = 1.2$ m., $v = 0.4$ m/s, $\phi = 180°$ when changing the position angle to θ= 0°, 30°, 45°, and 60°.

a position angle θ is an angle between the object and sound source as shown in Figure 5. We set up the distance $d = 1.2$ m. and $\theta = 20°$. In Figure 5, the velocity of the target was changed by the motorized stage. The probability distributions of the velocity measurement, which were determined from the peak intervals shown in Figure 2 , were measured at both microphones shown as Figure 6. The distribution was 200 times. The room temperature when performing the measurement was 25.5°C and the propagation speed of the ultrasound in the air was approximately 346.7 m/s. It appears that the key aspect is the impact of the changes in room temperature and fluctuations in the air. Afterward, TOF was computed by Doppler-shift compensation [15]. When the Doppler-shift compensation TOF was achieved, the position angle θ and distance d were computed in Equations (1) and (8).

The results of object position can be illustrated in Figures 7a and 7b. In this experiment, it is observed that there is no impact to such a flying object because the angle error was under approximately 0.02° degree. In addition, the

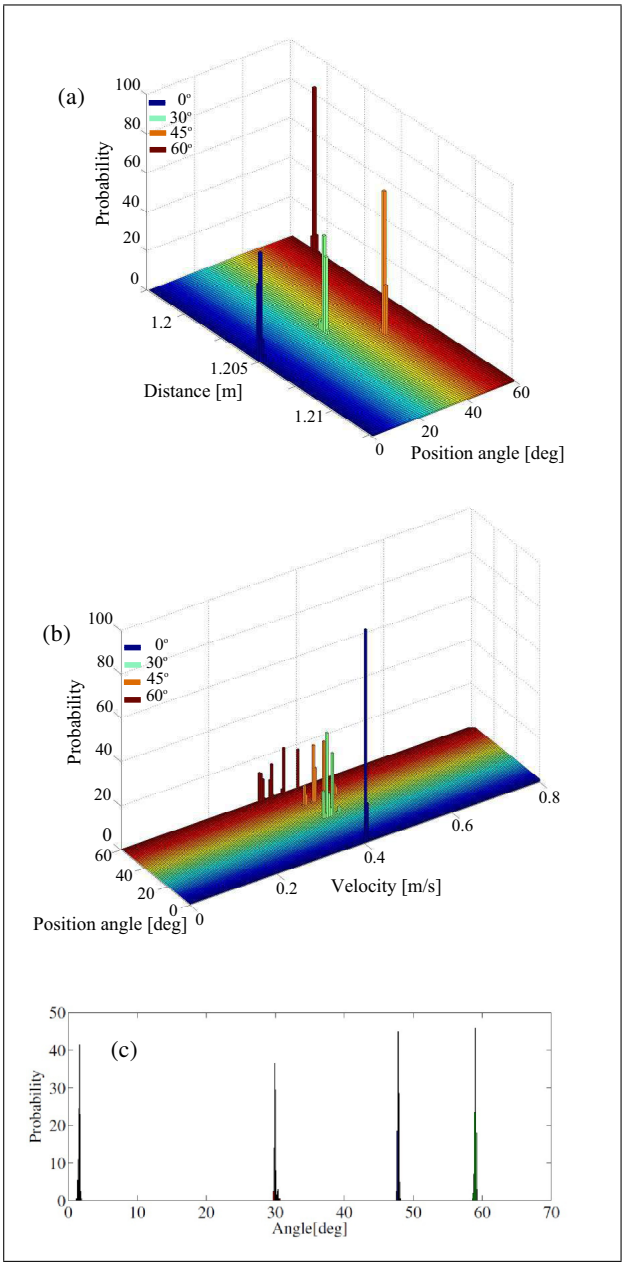

Figure 10. Distributions of changing the position angle to 0°, 30°, 45°, and 60° m/s at distance = 1.2 m and velocity = 0.4 m/s (a) distance distributions (b) velocity distributions (c) position - angle distributions.

distance errors from the measurements were under ±1 cm. For the velocity measurement, the absolute velocity due to both microphones was estimated by the two-dimensional velocity vector measurement depicted in Figure 7c.

3.2.2. Experimental results of the object position and velocity measurement obtained by varying the position angle of the target

In this experiment, assuming that the position angle θ of the object was changed, to verify the distance d, the effect of the speed of the target is shown in Figure 8. The setting of the distance d and the speed was constantly fixed with 1.2 m and 0.4 m/s. between the speaker and the target. The position angles θ incident on the object were 0, 30, 45, and 60°. Again in Figure 9, the probability distributions of the velocity measurement, when the position angle θ was changed, were measured at both microphones. The distance distribution shown in Figure 10a had errors under 1 cm. In Figure 10c, the position angle θ was determined in the form of the position angle distribution by measurements. The influence of the position angle distribution, when compared with the act ual value, was quite small. For the velocity measurement in Figure 10b, when the position angle θ of the moving object between the sound source and the two microphones was increased, the dispersion of the results became larger. As a result, examining in Figure 10b again, we estimated v_1 and v_2 on the dotted lines of x and y, not the actual line of microphone-1 and microphone-2, they provided more accuracy if the angle of the target was closer to 0°. Thus, the diff erence between the Doppler velocity obtained from both microphone was larger when the position angle θ was larger.

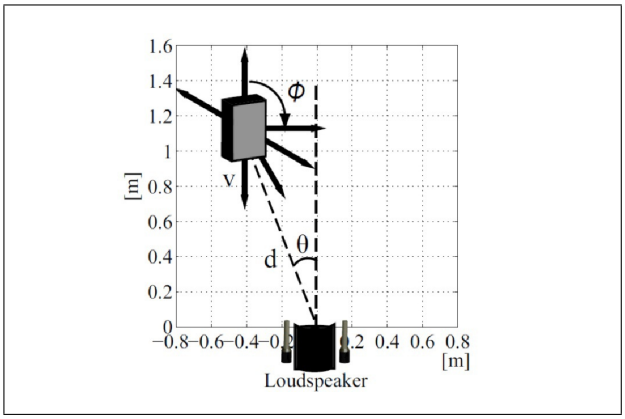

Figure 11. Distance d = 1.2 m, the object position $\theta = -20°$ v = 0.4 m/s when changing direction of the direction angle to ϕ of the target to 0°, 90°, 120°, 150°, 180°, and −60°.

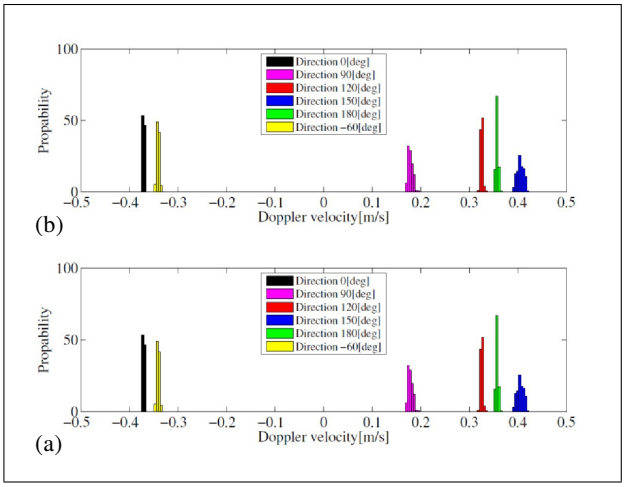

Figure 12. The velocity measurement (a) left microphone (b) right microphones at d = 1.2 m, v = 0.4 m/s, θ = 120° when changing the direction angle to ϕ.

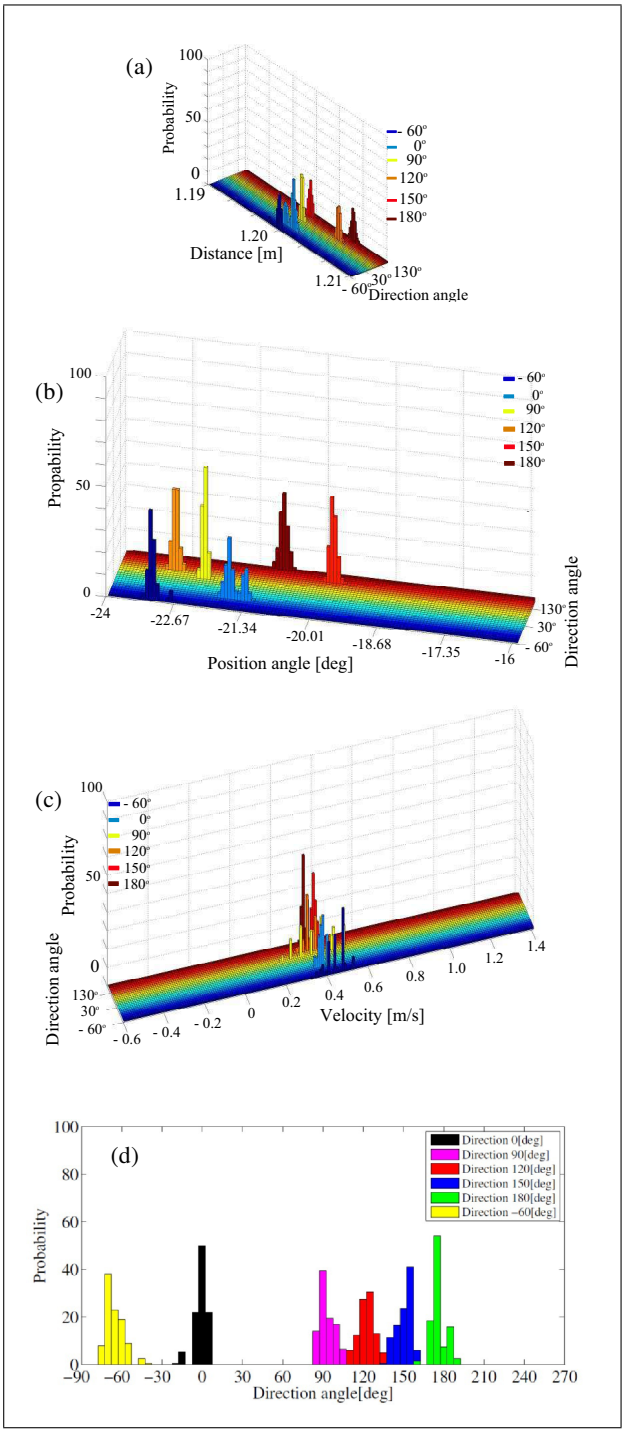

Figure 13. Distributions of changing the position angle to 0°, 30°, 45°, and 60° m/s at distance = 1.2 m and velocity = 0.4 m/s (a) distance distributions (b) position - angle distributions (c) velocity distributions (d) direction - angle distributions.

3.2.3. Experimental results of the object position and velocity measurements in the case of changing the direction angles of the target

Another verification of the ultrasonic position and velocity measurement method by the proposed method is shown in Figure 10, which covers when the direction angle ϕ was changed to 0, 90, 120, 150, 180, −60 degrees. In this case, an experiment was performed that assumed that the distance d was 1.2 m, position angle θ was −20°, and the object velocity v was 0.4 m/s. The distribution of the Doppler velocity obtained from the received signal of the microphone is shown in Figure 12. The measured distance distributions are pictured in Figure 13a. It was shown that errors were less than 2 cm. The position-angle distributions were evaluated in Figure 13b. Moreover, in Figure 13c, the velocity distributions were pictured for many cases of direction angle. However, when scrutinizing in the case of $\phi = -60$, 90, and 120°, the accuracy in the velocity had wide distributions compared with $\phi = 0$, 150, and 180°. The reason was that we used the square-shape rigid body as the object. When object did not turn the face to the microphones. We used the definition of the intersection point between v_1 and v_2 for the velocity measurement. It was a main point of deviation. This approach provided more accuracy if the direction angle ϕ and the bisector were closer. Finally, the direction-angle distributions were shown as Figure 13d.

4. Conclusion

An over-sampling signal processing method of two-dimensional ultrasonic distance and velocity measurements using a pair of LPM signals has been proposed. The proposed method consists of cross correlation by single-bit signal processing and low-calculation-cost Doppler-shift compensation. Moreover, a recursive cross-correlation is being implemented in FPGA because ultrasonic two-dimensional position and velocity measurement for real-time applications were required in these experiments. The velocity measurement of a moving object uses an idea of a peak interval of a cross-correlation function. Afterward, the absolute velocity was estimated by the velocity vector measurement. The accuracy of the ultrasonic two-dimensional position and velocity while using two microphones with two cycles of LPM signals was examined by experiments. The experiments were executed under three different conditions, 1) varying the speed of the target, 2) varying the position angle of the target, and 3) changing the direction angle of the target. A high accuracy regarding the ultrasonic position and velocity measurement was obtained in the case of the narrow angle position between the object and sound source. Conversely, there was the dispersion of the velocity results if a large-angle position was given. For future work, multiple moving objects in the area will be considered.

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