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High accuracy measurement of small movement on object using airborne ultrasound
空中超音波を用いた物体上の微小振動の高精度計測

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1. Introduction

Acoustic sensing in air has the potential to obtain various information about a surrounding object such as its position, shape, material and movement. Therefore, the advance of acoustic measurement techniques is required. We have examined the reflection characteristic of human body, and showed that breath in the standing position and heart beat in the supine position can be measured [1].

To measure human breath and heart beat stably, it is important to evaluate measurement error distribution of small movement using acoustic signal. In this paper, we estimate the error of human surface movement quantitatively for the measurement using M-sequence signals, MTI filter, and phase tracking. Phase tracking after MTI filter causes offset error in the measurement of small movement on the body surface like the heart beat[2]. We also present error reduction technique to realize high accuracy measurement of small movement like the heart beat.

2. Distribution of the measurement error

2. 1 Theoretical analysis

The theoretical distribution of measurement error was estimated when using MTI filter and phase difference. The k-th received signal that measured successively is defined as

$$p_k(t) = s_k(t) + r_k(t) + n_k(t),$$

where $s(t)$ is the reflected signal from the target, $r(t)$ is reverberation signal, and $n(t)$ is ambient noise. Processed results by MTI filter, m_k is given by

$$m_k = p_{k+1}(\mathrm{t}) - p_k(t).$$

Then m_k is converted to M_k that is the complex notation by quadrature demodulation. Next, the result of phase tracking that is calculated by $M_2 \times \mathrm{conj}(M_1)$ is shown as

$$\begin{aligned} c &= 4\sin^2\frac{d\theta}{2}\cdot e^{jd\theta} - \frac{1}{2}\cdot\frac{2\sigma^2}{A^2} \\ &\quad + \frac{\sqrt{2}\sigma}{\mathrm{A}}\cdot\sqrt{\frac{3}{4}\cdot\frac{2\sigma^2}{A^2} + 4\sin^2\frac{d\theta}{2}}\cdot N \\ &\quad + \frac{\sqrt{2}\sigma}{\mathrm{A}}\cdot 2\sqrt{2}\sin\frac{d\theta}{2}\cdot e^{j\frac{\pi+d\theta}{2}}\cdot\left(\mathrm{real}(N')\right). \quad (1) \end{aligned}$$

$d\theta$ is the phase difference of reflected signals at times of successive measurements. A is the amplitude of $s(t)$, σ is the standard deviation of $n(t)$, therefore $\mathrm{A}/\sqrt{2}\sigma$ is the SN ratio of $p(t)$. N and N' are 2-D Gaussian noise distribution on complex plane that standard deviation is 1. **Figure 1** is the schematic diagram of c that plots on complex plane. (a), (b), (c) and (d) in **Fig. 1** correspond to 1st, 2nd, 3rd and 4th terms in Eq. (1). Summation of (a)-(d) become elliptical distribution as shown in **Fig. 1**.

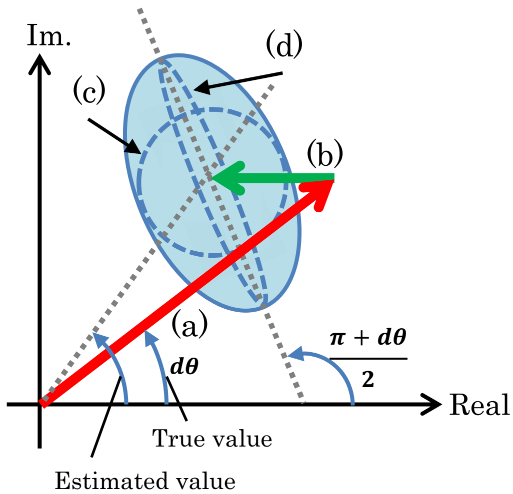

Fig. 1 Schematic diagram of the processing in the complex plane

2. 2 Measurement error

We simulated about tracking the target based on Eq. (1). **Figure 2** shows the complex plot of Eq. (1) and probability density distribution of phase in case $\mathrm{A}/\sqrt{2}\sigma$ is 8 dB and $d\theta$ is $8/3\pi$. This figure also shows estimated value and true value. There is an offset error between estimated value and true value. **Figure 4 (a)** shows the 2-D plot of error between estimated value and true value with changing $\mathrm{A}/\sqrt{2}\sigma$ and $d\theta$. Error becomes larger in case of lower SN ratio or smaller $d\theta$.

3. Method of error reduction

We examined the method of error reduction. Phase difference was calculated as $M_2 \times \mathrm{conj}(M_1)$. From this calculation, offset error in estimated movement occurs. If we can estimate the standard deviation of ambient noise, we can cancel the offset error in phase difference using the calculation of

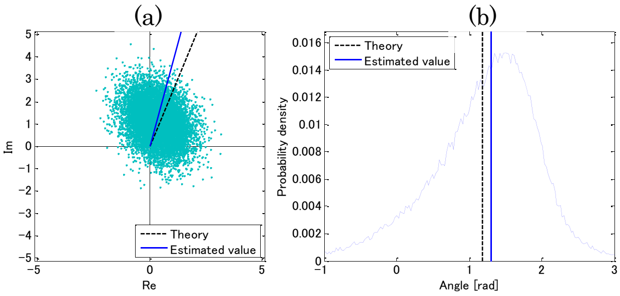

Fig. 2 Simulation data (SN ratio : 8 dB, $d\theta = \frac{8}{3}\pi$) (a) Complex plot (b) Probability density distribution of angle

$M_2 \times \mathrm{conj}(M_1) + \sigma^2$. This process is indicated as a modified vector, (b) in **Fig. 1 (b)**. Using this simple processing, we can improve the target movement estimation. **Figure 3** shows the complex plot and provability density distribution of phase after the improvement, in case $A/\sqrt{2}\sigma$ is 8 dB and $d\theta$ is $8/3\pi$, and also shows estimated value and true value. **Figure 4 (b)** shows the 2-D plot of error between estimated value and true value after the improvement with changing $A/\sqrt{2}\sigma$ and $d\theta$. Error was reduced in case SN ratio is low and $d\theta$ is small. **Figure 5** shows the enlarged view of **Fig. 4** and the phase difference in case of breath and heart beat with measurement interval 200 ms. Ultrasound frequency is 25kHz. From Fig. 5(a) and (b), error is reduced and it is possible to measure the heart beat amplitude clearly.

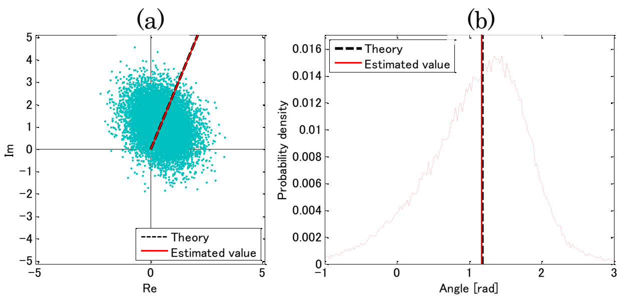

Fig. 3 Simulation data after the process (SN ratio : 8 dB, $d\theta = \frac{8}{3}\pi$) (a) Complex plot (b) Probability density distribution of angle

4. Conclusion

We presented theoretical error analysis for high accuracy measurement of small movement using MTI filter and phase tracking. We also presented error reduction technique to realize high accuracy measurement of small movement like the heart beat.

References

1) R. Fukushima *et al*: Proc. of autumn meeting of ASJ (2010), 1431-1432.

2) K. Hoshiba *et al*: IEICE Technical Report, vol. 111 (2012), 29-34.

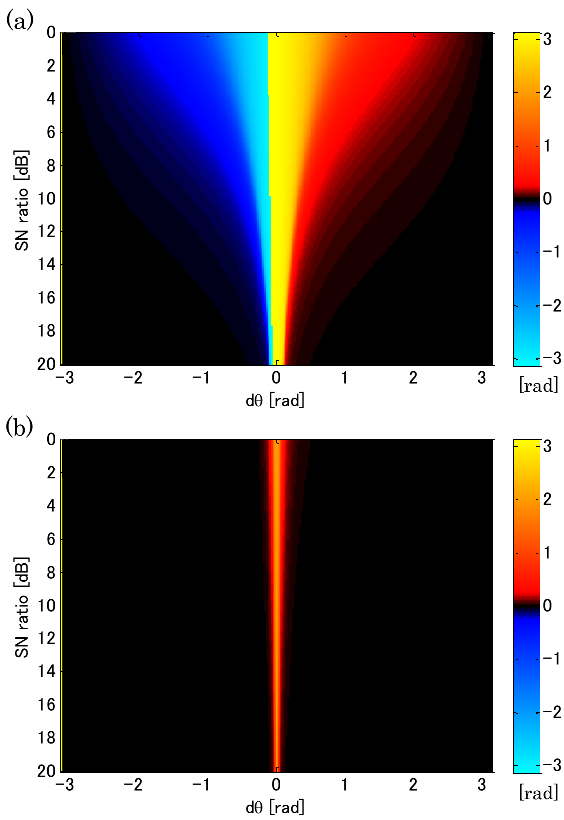

Fig. 4 Error of estimated value

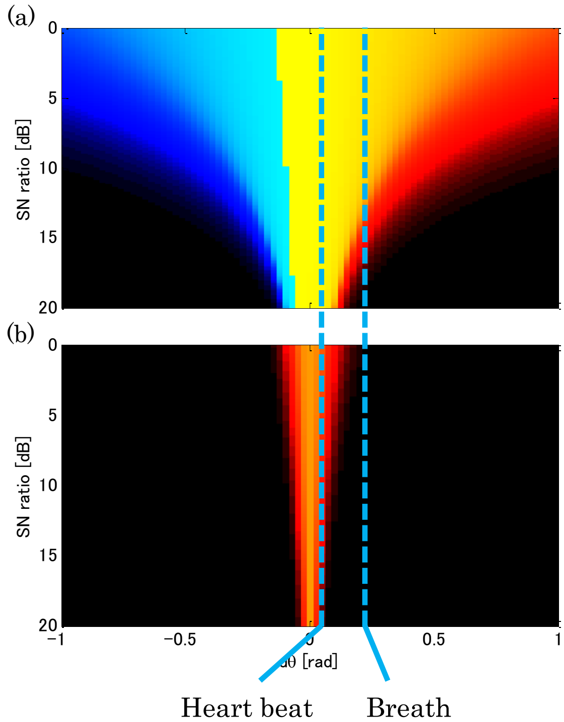

Fig. 5 Error of estimated value and indication of breath and heart beat