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Estimation of Elevational Distance Between Image Planes by Analysis of Echoes from Point Scatters
点散乱体からの超音波信号の解析による
断層像間のスライス方向距離推定

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1. Introduction

There are two approaches to the three-dimensional image reconstruction using a 1-D array ultrasonic transducer: mechanical linear scanning and free-hand scanning. Mechanical scanning employs a motorized mechanism to translate the transducer linearly. When the transducer is moved, 2-D images are acquired at constant spatial intervals (typically 0.2 mm in 3-D carotid ultrasound imaging [1]). However, the large size of the scanning system and its weight sometimes make it inconvenient to use [1]. In free-hand scanning, a sensor (e.g., electromagnetic or optical) is attached to the transducer to measure the position and orientation of the transducer. However, electromagnetic interference (e.g., highly conductive metals, a.c. power cabling and motors) degrades the accuracy of position tracking (2.9 ± 1.0 mm in location in a surgical environment [2]). Furthermore, the line-of-sight between the position sensor and tracking tool needs to be maintained for successful optical tracking [3]. To overcome these problems, we propose a novel method using the phase shift between ultrasonic RF echoes.

2. Principles

In this study, the elevational distance between two 2-D US images was estimated using the phase shift properties of echoes from a point scatter, by assuming that there are many point scatters in the tissue. To do that, we evaluated the phase shift properties of the echo signals from a point scatter (fine wire). Point scatters in a target (silicone phantom), which is mimicking tissue, was used to determine elevational distance by referring to the phase shift property of a point scatter.

As illustrated in Figure 1, it is assumed that the difference Δr of the propagation distance between the echo $rf(x, y, z)$ at elevational position $y = 0$ and the echo $rf(x, y+\Delta y, z)$ at $y = \Delta y$ is given by the phase shift $\Delta\theta(f_0; x, y, z)$ of $rf(x, y+\Delta y, z)$ from $rf(x, y, z)$ as follows:

$$\Delta r = \frac{c_0}{4\pi f_0}\Delta\theta(f_0; x, y, z)\ , \tag{1}$$

$$\Delta y = \sqrt{(z_0+\Delta r)^2 - z_0^2}\ , \tag{2}$$

where c_0 and f_0 are sound speed of water and center frequency, respectively. By solving the Pythagorean theorem (eq. (2)), the elevational displacement Δy is estimated from the measured phase shift $\Delta\theta(f_0; x, y, z)$.

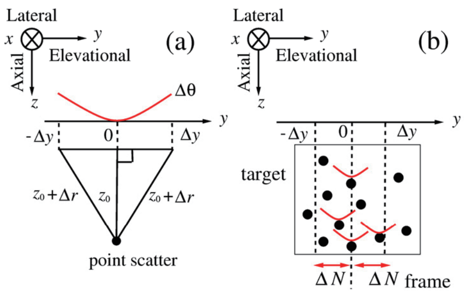

Fig. 1 Scanning along elevational direction

2.1 Estimation of phase shift by cross spectrum

The phase shift $\Delta\theta(f_0; x, y, z)$ is calculated from frequency spectrum $Y(f_0; x, y, z)$ and $Y(f_0; x, y+\Delta y, z)$ of RF echoes $rf(x, y, z)$ and $rf(x, y+\Delta y, z)$ as follows [4]:

$$e^{\Delta\theta(f_0;x,y,z)} = \frac{Y^*(f_0;x,y,z)Y(f_0;x,y+\Delta y,z)}{\left|Y^*(f_0;x,y,z)Y(f_0;x,y+\Delta y,z)\right|} \tag{3}$$

In this study, frequency spectrum $Y(f_0; x, y, z)$ is at lateral beam position x, elevational position y, by extracting RF signal with a Hanning window of a length of 425 ns in the depth direction centered at depth z. The frequency of interest f_0 was set as 9.4 MHz, which almost corresponds to the center frequency of RF echo.

2.2 Determination of point scatter's positions

The elevational position of a point scatter was determined by means of root-mean-squared (RMS) error $\varepsilon(\Delta y; x, z)$ between estimated and actual phase shift at lateral position x and depth z as follows:

$$\varepsilon(\Delta y; x, z) = \sqrt{\frac{1}{(2\Delta N+1)}\sum_{i=-\Delta N}^{\Delta N}\left(\Delta\theta(f_0; x, y+i\cdot\delta y, z) - \Delta\theta_T(y+i\cdot\delta y)\right)^2}\ , \tag{4}$$

$$\Delta\theta_T(y+i\cdot\delta y) = \frac{4\pi f_0}{c_0}\Delta r_T(y+i\cdot\delta y), \tag{5}$$

where $\Delta r_T(y+i\cdot\delta y)$ is the actual displacement.

3. Basic Experimental Results

3.1 Experimental system

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As illustrated in Figure 2, the elevational positions of a wire and phantom were measured by basic experiments. The phantom was made with silicone rubber which contained graphite powder (ϕ75 ~ 106 μm). The wire was measured at a frame rate of 165 Hz and moved by an automatic XYZ stage at a constant speed of 660 μm/s resulting an elevational distance δy of images in two consecutive frames of 4 μm. On the other hand, the silicone phantom was measured at a frame rate of 61 Hz and moved at every 100 μm a constant speed of 6100 μm/s (typical freehand scanning speed [5]). RF data were acquired using a 10 MHz conventional linear-type probe of ultrasonic diagnostic equipment (Aloka, SSD-6500). The sampling frequency of the RF signal was f_s = 40 MHz and the sound speed in the water at 20 degrees was c_0 = 1485 m/s (Willard's experimental eq. [6]).

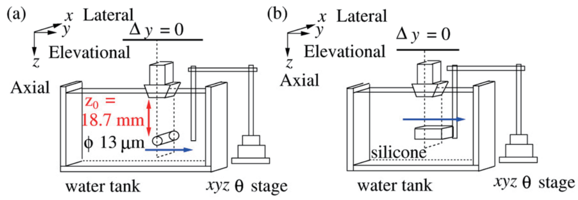

Fig. 2: Schematic of system for basic experiments.
(a) ϕ13 μm wire. (b) Silicone phantom.

3. 1 Measured phase shift of echo from the wire

Figure 3 shows the RF signals and phase shift between RF echoes from the wire. The red curve in Fig. 3(b) shows the theoretical phase shift (eq. (5)), and the blue curve shows experimental one. It is confirmed that the experimental phase shift is similar to the theoretical one. Therefore, we use theoretical phase shift (eq. (5)) for estimation of the elevational distance of the phantom.

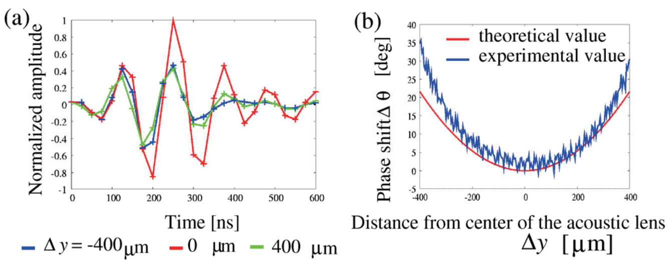

Fig. 3: (a) RF signals from the wire. (b) Phase difference.

3. 2 Determination of point scatter in phantom

Figure 4 shows a B-mode image of the phantom and RMS errors between the theoretical and estimated elevational distances. The number of measurements of phase shifts, ΔN, was set at 4 [$2\Delta N \times (\delta y$ = 100 μm) < (elevational beam width = 820 μm)].

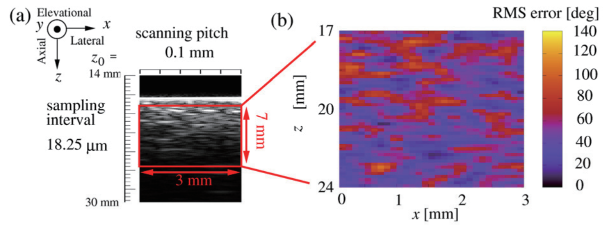

Fig. 4: (a) Silicone B-mode image. (b) RMS errors between estimated and theoretical phase shifts.

It is confirmed that there are positions with less RMS errors despite of the ROI position. Scatters at positions with low RMS errors are considered to have a phase shift property similar to that of a point scatter.

3. 3 Estimation of Elevational distance

Figure 5 shows the difference (errors) of the estimated elevational distances between images.

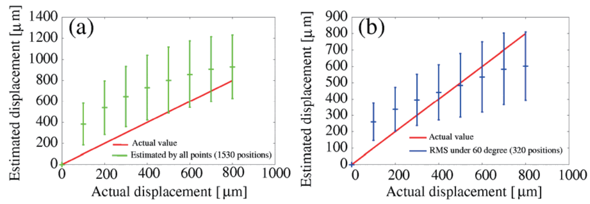

Fig. 5 (a) Estimated elavational distance by all points.
(b) Points with RMS errors under 60 degree.

By using positions which show phase shift properties similar to that of a point scatter, the elevational distance between images were determined with errors, which were smaller than those obtained by the electromagnetic or optical methods.

4. Conclusion

In this study, we investigated a method of estimation of the elevational distance between images. The proposed method showed potential for the estimation of the distance in the elevational direction using the phase shift properties of echoes.

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