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Relationship between ultrasonic transmitted beamwidth and accuracy for measurement of myocardial minute velocity

心筋の微小速度計測のための超音波送信ビーム形状と計測精度の関係

Kana Sugahara[1†], Shohei Mori[2], Mototaka Arakawa[1,2], and Hiroshi Kanai[2,1] ([1]Grad. School Biomed. Eng., Tohoku Univ.; [2]Grad. School Eng., Tohoku Univ.)
菅原 佳奈[1†], 森 翔平[2], 荒川 元孝[1,2], 金井 浩[2,1] ([1]東北大院 医工, [2]東北大院 工)

1. Introduction

Echocardiography is useful in the diagnosis of the cardiac function because of noninvasive. Myocardium dynamics are fast and complicated. Thus, high-resolution measurements are needed in both space and time domains. However, because of the trade-off relationship between the high spatial resolution and the high frame rate, it is not easy to determine the optimal ultrasound transmitted conditions for the diagnosis of the cardiac function.

In our research group, we have proposed an experimental method to determine the optimal transmitted conditions of the beamwidth and the frame rate [1]. We constructed the water-tank experimental system that is designed to measure minute velocity waveforms simulating the myocardium movement. We tried to quantitatively evaluate the measurement accuracy of the velocity. However, the measurement error was large though the target was displaced with a single frequency and the ultrasound transmitted conditions are considered to be sufficient to measure the target velocity. In the present study, we reconstructed the measurement system to improve the accuracy of the quantitative evaluation.

2. Method

2.1 Dependence of minute velocity measurement accuracy on transmitted conditions

The accuracy of the minute velocity measurement by the ultrasound is affected by the transmitted beam conditions. The larger the angular width of the transmitted beam, the lower the SN ratio of the transmitted and received ultrasound beam. Moreover, the spatial resolution is lowered and the measurement is affected by the surrounding tissues. These cause an increase in the measurement error. As the frame rate decreases, the measurement error increases since the high-frequency components of the minute velocity cannot be measured. Since the higher frame rate requires the wider beamwidth in the high-density receive beamforming, there is a trade-off relationship between the high spatial resolution and the high frame rate, and the measurement error in velocity is expected to be minimized under the optimal beam transmitted conditions.

2.2 Minute velocity measurement

In the present study, the minute velocity in the beam direction was measured using the phased tracking method [2]. The average of the minute velocities between consecutive two frames at a frame rate FR [Hz] is given by

$$\hat{v}\left(t+\frac{1}{2 \cdot FR}\right)=-\frac{c_0}{4\pi f_0} FR \cdot \Delta\theta, \qquad (1)$$

where c_0 is the speed of sound in the medium, f_0 is the center frequency of the ultrasonic received signal, and $\Delta\theta$ is the phase difference of the received signal between two frames. In the present study, f_0 was obtained from each received RF signal.

2.3 Experimental method

The experimental system is shown in **Fig. 1**. The vibration velocity of the urethane phantom surface was measured by ultrasound, and the velocity $\widehat{v_U}(n)$ was obtained by applying Eq. (1) to the received signal measured on the center of the phantom surface. As the reference, the velocity $v_L(n)$ was measured by a laser Doppler velocimetry. The measurement error by the ultrasound, $\sqrt{e^2}$, was evaluated using Eq. (2), where N is the number of samples in the velocity waveform.

$$\sqrt{e^2}=\frac{\sqrt{\sum_{n=0}^{N-1}\{\widehat{v_U}(n)-v_L(n)\}^2}}{\sqrt{\sum_{n=0}^{N-1}\{v_L(n)\}^2}}. \qquad (2)$$

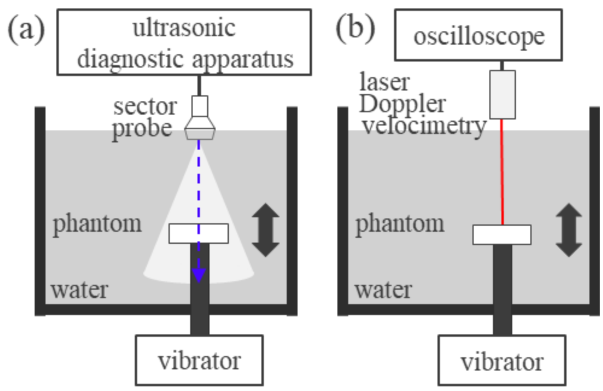

Fig. 1. Schematic diagram of the experimental system. (a) Ultrasonic measurement, (b) Laser Doppler velocimetry measurement.

Email address: k.sugahara@ecei.tohoku.ac.jp

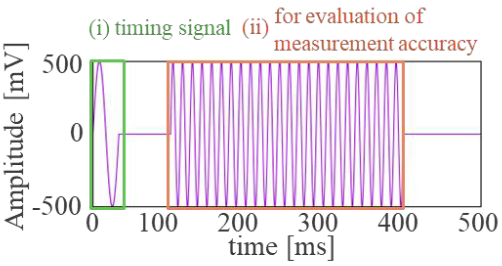

Fig. 2. The input voltage to the shaker.

In the present study, the target velocity was measured by the ultrasound and the laser Doppler velocimetry at the same position. To measure at the same position, it is necessary to measure both measurements at different timings. By setting the input signal to the shaker as shown in **Fig. 2**, the trigger signals measured by the ultrasound and the laser Doppler velocimetry at different timing were synchronized on the computer. After the synchronization, the measurement error was evaluated for the received signals for the input signal shown in Fig. 2(ii).

3. Experiment

3.1 Experimental condition

For simulating the *in vivo* measurement, a urethane phantom surface was placed at depth of $d = 50$ mm from the probe surface and was vibrated up and down with a shaker (Type 4810, Brüel & Kjær). The vibration frequencies were set as 50, 80, and 100 Hz, respectively. The ultrasound diagnosis apparatus (Prosound α-10, ALOKA) was used. The plane wave was transmitted with a nominal center frequency of 3.75 MHz. The *FR* was 1,683 Hz. The laser Doppler velocimetry (LV-1300, Ono Sokki) and the oscilloscope (TBS2104, Tektronix) were used.

3.2 Result and Discussion

The velocity waveforms in 200 ms were used to evaluate the measurement error. Only the signals in 50 ms are plotted in **Fig. 3**. The waveforms measured by the ultrasound corresponded to those measured by the laser Doppler velocimetry. The measurement errors $\{\sqrt{\overline{e^2}}\}$ were 2.3% at 50 Hz, 4.0 % at 80 Hz, and 5.3 % at 100 Hz, respectively, as shown in **Fig. 4**. All measurement errors were lower than those obtained in the previous experimental measurement system [1] (it was 11% at a vibration frequency of 30 Hz). Thus, the quantitative accuracy of the evaluation was improved.

As shown in Fig. 4, the higher the vibration frequency, the larger the measurement error. To examine the cause, the relationship between the velocity waveforms measured by the ultrasound and the laser Doppler velocimetry was investigated. The results for vibration frequencies of 50 and 100 Hz are shown in **Fig. 5**. In Fig. 5(b), the velocity measured by the ultrasound deviated from that measured by the

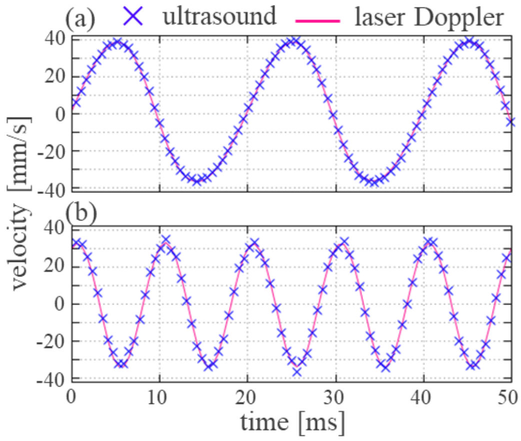

Fig. 3. Measured minute velocity waveforms. Vibration frequencies are (a) 50 Hz and (b) 100 Hz.

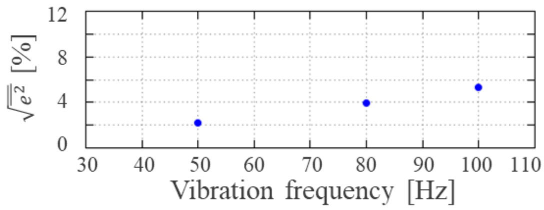

Fig. 4. Vibration frequency and measurement error.

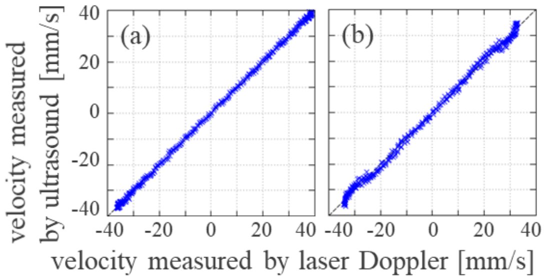

Fig. 5. Relationship between two velocity waveforms. Vibration frequencies are (a) 50 Hz and (b) 100 Hz.

laser Doppler velocimetry when the absolute value of the target velocity was large. We will investigate the cause of the decrease in the accuracy for the large velocity of the object as the vibration frequency increases in future.

4. Conclusion

The velocity of the vibrated phantom surface was measured at the same position in the ultrasound and the laser Doppler velocimetry by synchronizing the measured velocity waveforms with the trigger signal. The measurement accuracy was improved compared to the previous study though the measurement error increased as the vibration frequency of the target object becomes high.

References

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