Influence of Beam Spot Size in Measurement of Pulse Waves at Multiple Parts of the Human Body Using Millimeter-wave Array Radar

Yuji Oyamada[1*] and Takuya Sakamoto[1,2]
[1] Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan
[2] PRESTO, Japan Science and Technology Agency, Kawaguchi 332-0012, Japan
[*] Corresponding author, email: oyamada.yuji.72a@st.kyoto-u.ac.jp

***Abstract*—This study evaluates the accuracy of measurements of cardiac pulse wave propagation using a 79-GHz millimeter-wave ultra-wideband multiple-input multiple-output array radar. The radar echoes from multiple parts of the human body were extracted using an array beamforming technique. The phase of each echo was converted to the skin displacement and its waveform was carefully compared with the waveform obtained using laser displacement sensors, which was used as a reference for evaluation of accuracy. Because the beam spot sizes of the radar and laser sensors were different, we applied smoothing to the waveform measured using the laser sensor, to make the effective beam spot size equivalent to the spot size of the array radar beam. We then quantitatively analyzed the relationship between body displacement waveforms measured using the array radar and laser sensors.**

***Keywords*—Millimeter-wave radar, array antennas, pulse wave velocity, laser displacement sensor.**

I. Introduction

The cardiac pulse wave is an elastic wave that propagates mainly along the arterial system, and its propagation velocity is related to diseases such as arteriosclerosis and hypertension [1], [2]. Therefore, continuous and long-term monitoring of pulse wave velocity is desirable for the early detection and treatment of various cardiovascular diseases. Michiler et al. [3] reported measurement of the pulse wave using a 24-GHz phased array radar that can direct its beam in multiple directions sequentially, which allows for the measurement of two body parts alternately. Their approach requires the target person to remain in a specific position with a specific posture, and is not therefore suitable for continuous and long-term monitoring. To avoid such constraints, we are developing a non-contact method for the measurement of body displacement at multiple body parts using a millimeter-wave (MMW) 12-channel multiple-input and multiple-output (MIMO) array radar system. To evaluate its accuracy in measuring the pulse wave, we conduct measurements using multiple laser displacement sensors. To compensate for the difference in beam spot sizes between the radar and laser sensors, we apply time-averaging to the displacement waveform obtained using the laser sensor. Using this approach, the displacement waveforms obtained using the radar and laser sensors are quantitatively compared to evaluate the accuracy of non-contact measurement of pulse waves using our proposed approach.

II. Measurement Using Array Radar System and Laser Displacement Sensors

In this study, we use a 79-GHz MMW MIMO array frequency-modulated continuous wave (FMCW) radar to measure cardiac pulse waves. The MIMO array consists of three transmitting elements and four receiving elements, resulting in a 12-element linear virtual array with an antenna spacing of half the wavelength. Let $\boldsymbol{s}(t)$ be the received signal vector and $\boldsymbol{a}(\theta)$ be the weight vector of the beamformer method for an angle of θ. The i-th directions of arrival (DOAs) θ_i $i = 1, 2, \cdots$ are estimated by finding local peaks of the angular profile $P_{\mathrm{BF}}(\theta) = \int |\boldsymbol{a}^{\mathrm{H}}(\theta)\boldsymbol{s}(t)|^2 \mathrm{d}t$. The i-th echo $y_i(t)$ is estimated as $y_i(t) = \boldsymbol{a}^{\mathrm{H}}(\theta_i)\boldsymbol{s}(t)$. The displacement of the i-th body part is obtained as $d_i(t) = \lambda/4\pi\angle y_i(t)$, where λ is the wavelength.

To evaluate the accuracy in estimating $d_i(t)$ using the radar system, we also use laser displacement sensors with a wavelength of 655 nm and a resolution of 0.2 μm. A pair of laser sensors are located approximately 150 mm from the skin surface, at the back and a calf of the participant. When the displacement waveforms measured using the two types of sensors are compared, we need to consider the beam spot sizes of the sensors; the spot size of the laser sensors is 120 μm in diameter, which is much smaller than the radar spot size.

III. Comparison of Displacement Waveforms Measured Using Radar and Laser Sensors

Figures 1 and 2 show the waveforms of the skin displacement at the back and a calf of a participant. The displacement $d_i(t)$ measured using the radar is shown in black, whereas the displacement $d'_i(t)$ measured using the laser displacement sensor is shown in red. In Fig. 1, the two curves show good agreement, with the normalized correlation coefficient being as high as 0.93. By contrast, the two curves in Fig. 2

show different waveforms, with a normalized correlation coefficient of only 0.52.

These results indicate that the body displacements measurements using the radar system and laser displacement sensors are consistent at the back of the participant, but not at the calf. The reason for this is discussed in the following text. Because the baseline length of the antenna array of the radar is 20.9 mm, the 3-dB beam width is 9.2° for a wavelength of 3.8 mm. As the distance to the target person is about 1.2 m, the footprint diameter is 19.2 cm, which is significantly different from the laser spot size of 120 μm.

The radar echoes are phase-modulated by the time-varying displacement of the body part covered by the radar footprint. The reflected waves from multiple points within the footprint interfere with each other and the apparent displacement is averaged. If we assume that a single arterial pulse wave propagates through the calf, the difference between the radar and laser spot sizes can be compensated for by time-averaging the displacement measured using the laser displacement sensor.

The blue dash-dotted line in Fig. 2 shows the smoothed displacement $h*d_i'(t)$ measured using the laser displacement sensor, where $*$ denotes a convolution, and h is a boxcar function with a time width of $T = 0.36$ s. Fig. 3 shows the normalized correlation between the moving average time width T and time lag τ. White points in Fig. 3 are the local maxima for each T. We see that by applying the time-averaging, the displacement $h * d_i'(t)$ becomes similar to the displacement $d_i(t)$ measured using the radar, and their normalized correlation coefficient is increased from 0.52 to 0.84, although the time lag τ at which the maximum correlation is achieved is not zero.

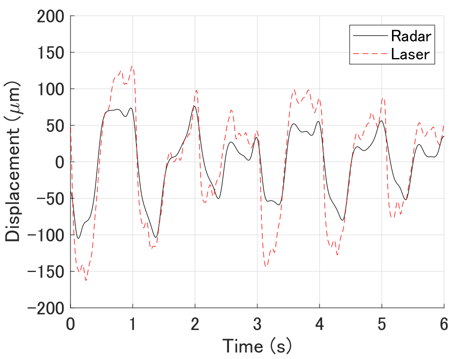

Fig. 1. Body displacement waveforms at the back measured using the radar (black) and laser displacement sensor (red).

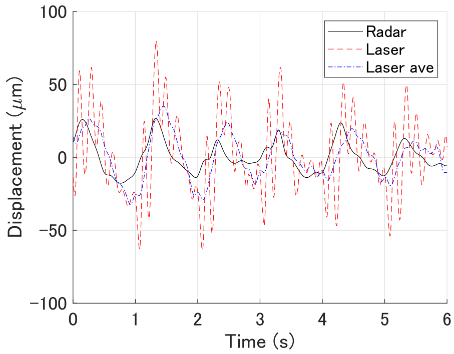

Fig. 2. Body displacement waveforms at a calf measured using the radar (black) and laser displacement sensor (red). The smoothed laser measurement is shown as a blue dash-dotted line.

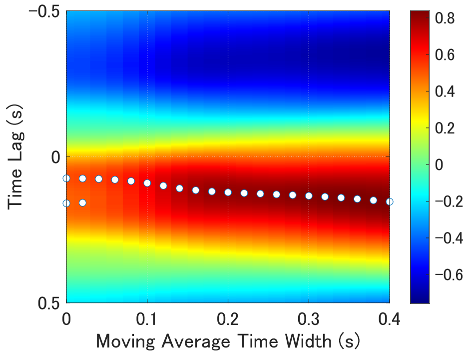

Fig. 3. Normalized correlation coefficients for various moving average time widths. White dots are the local maxima for each time width.

IV. Conclusion

In this study, we evaluated the differences between skin displacement waveforms measured using the MMW MIMO array radar system and those measured using laser displacement sensors. The displacement waveforms at the back of the participant were in good agreement, with a normalized correlation coefficient of 0.93, whereas the waveforms at a calf showed discrepancy, with a normalized correlation coefficient of 0.52. Assuming a model where the pulse wave propagates in only one direction, we applied time-averaging to the displacement waveform measured using the laser displacement sensor, so that the difference between the spot sizes of the radar and laser beams can be compensated for. The results show that the normalized correlation coefficient between the waveforms was improved from 0.52 to 0.84 when the proposed time-averaging was used.

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