Adaptive Array Processing for Radar Measurements of Pulse Wave Propagation

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***Abstract*—Adaptive array processing techniques are investigated for their applicability to radar measurements of multiple body positions with displacements induced by propagating pulse waves. Unlike conventional settings for direction-of-arrival (DOA) estimation problems, body displacements arising from the pulse waves are modeled as having the same waveform with a certain time delay, which results in a signal correlation depending on the pulse wave velocity and waveform of the pulse. In measurements of pulse waves, we compare different adaptive array techniques in terms of their resolution and accuracy.**

***Keywords*—Adaptive array, array radar, pulse wave propagation, biomedical engineering.**

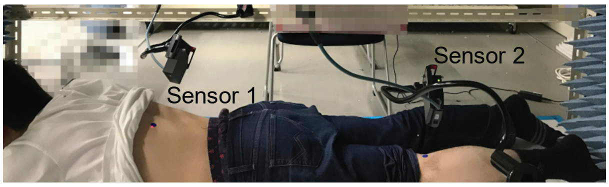

Fig. 1. Photograph showing the body locations of the two sensors for measurements of the displacements. During the process, the participant is lying in the prone position.

I. Introduction

Establishing a simple and non-invasive approach to the long-term monitoring of propagating pulse waves is key to early diagnoses of various cardiovascular diseases. The pulse wave is an elastic wave that propagates to the periphery as the heart contracts. Pulse wave velocity (PWV) can be used as a predictor of arterial stiffness. Many of the conventional studies on the measurement of PWV involve the use of contact-type sensors [1], [2], which are unsuitable for long-term monitoring. Therefore, radar-based noncontact measurements of pulse waves is preferable for this purpose. Some radar-based PWV measurements [3], [4] use contact sensors in addition to radar. There are only a few studies measuring the pulse waves using a single array-radar system without any contact-type sensors [5]–[7]. Among them, Oyamada and colleagues [6] used a simple Fourier-based beamforming (BF) technique, whereas Sakamoto [7] used a technique called physiological component analysis, which formulates the blind signal separation as an optimization problem with an objective function describing the prior physiological knowledge. Despite these efforts, there are still questions regarding which array processing techniques are suitable for resolving echoes modulated by the propagating pulse waves. This study investigates the performance of conventional adaptive array processing techniques when applied to radar echoes using an actual body displacement that is measured using a laser displacement sensor.

II. System Model

We assume a radar signal of a center frequency f and wavelength λ with an N-element linear antenna array with antenna spacing $d_0 = \lambda/2$. Let $x_n(t)$ be the signal received using the n-th element ($n = 0, 1, \cdots, N-1$). The signal vector $\boldsymbol{x}(t)$ is defined as $\boldsymbol{x}(t) = [x_0(t), x_1(t), \cdots, x_{N-1}(t)]^{\mathrm{T}}$. The received signal is assumed to be the summation of echoes $s_1(t)$ and $s_2(t)$ from two body positions 1 and 2, for which the incident angles are θ_1 and θ_2, respectively. The echo $s_j(t)$ ($j = 1, 2$) is phase-modulated by the displacement waveform $d_j(t)$ as $s_j(t) \propto \mathrm{e}^{\mathrm{j}2kd_j(t)}$, $k = 2\pi/\lambda$ is a wave number for wavelength λ. In our simulation, the displacements of body positions 1 and 2 are assumed to be $d_1(t) = d(t)$ and $d_2(t) = d(t - t_0)$, where t_0 is the pulse transit time (PTT) between the body positions. To ensure the waveform $d(t)$ is realistic, we measured the skin displacements using laser displacement sensors (Fig. 1), while the participant is lying in the prone position.

As a result, $x_n(t) = A_1\mathrm{e}^{\mathrm{j}2kd_1(t)}\mathrm{e}^{\mathrm{j}knd_0\sin\theta_1} + A_2\mathrm{e}^{\mathrm{j}2kd_2(t)}\mathrm{e}^{\mathrm{j}knd_0\sin\theta_2}$ is obtained, where A_1 and A_2 are complex amplitudes. Fig. 2 shows an example of displacement waveforms $d(t)$ (black) and $d(t - t_0)$ (red) for $t_0 = 83.3$ ms. In this study, we set $f = 79$ GHz, $\lambda = 3.8$ mm, $N = 4$, $A_1 = A_2 = 1$, $\theta_1 = 7.13°$, $\theta_2 = -4.76°$, and $S/N = 30$ dB.

III. Estimation of Directions of Arrival (DOA)

Under the conditions given in the previous section, we performed simulations to obtain the angular spectra of various adaptive array processing techniques. Assuming the target person is located at a distance 1.2 m from the array baseline, the reflection positions are 0.15 m and -0.10 m, respectively. We set three different PWV values 3, 10, 30 m/s, which resulted in the PTT values 83.3, 25.0, 8.3 ms, respectively, because the distance between the reflection points is 0.25 m.

The angular spectra of the BF, the Capon method, and MUSIC method were obtained, (Fig. 3; upper, middle, lower

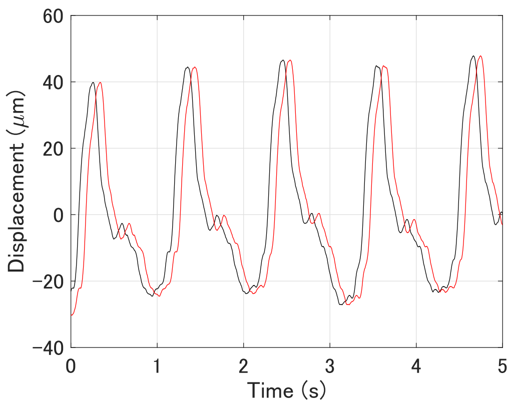

Fig. 2. Displacement waveform $d(t)$ (black) measured using laser displacement sensor and $d(t - t_0)$ (red) for PTT $t_0 = 83.3$ ms.

panels, respectively). The actual DOAs θ_1 and θ_2 are marked as black dashed lines in each panel. We see that the slower the PWV becomes, the higher the resolution becomes. For the Capon method, the two signals are resolved for PWV $= 3$ m/s, whereas the signals cannot be discriminated for PWV $= 10$ and 30 m/s. For the MUSIC method, the signals are resolved for all PWV $= 3$, 10 and 30 m/s. However, the signal for PWV $= 30$ m/s is better resolved. The average root-mean-square (RMS) DOA estimation errors for the Capon method are $0.8°$, $5.9°$, and $5.9°$ whereas for the MUSIC method the RMS errors are $0.1°$, $0.2°$, and $0.4°$ for PWV $= 3$, 10 and 30 m/s, respectively. The results indicate that the accuracy improves for small PWVs using the MUSIC method.

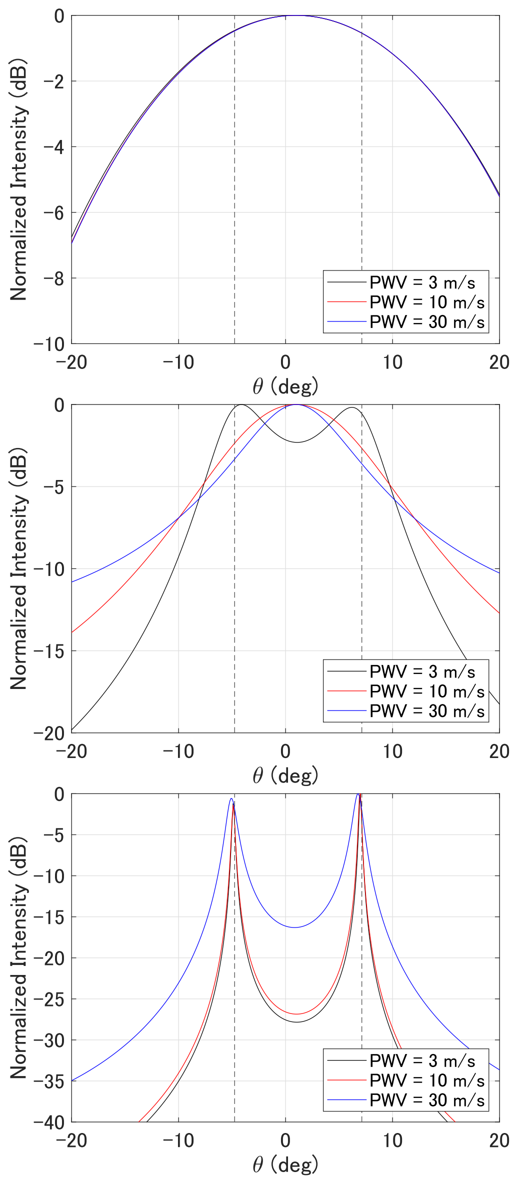

Fig. 3. Angular spectra of the BF, Capon and MUSIC methods.

IV. Conclusion

We investigated the applicability of the adaptive array processing techniques (the Capon and MUSIC methods) to radar measurements of two body positions with displacements induced by pulse waves. The results show that the resolution is dependent on the PWV value, and the signals are well resolved well for small PWVs. We are planning to perform experiments and investigate the accuracy of our physiological component analysis in comparison with existing adaptive array processing algorithms.

Acknowledgment

This study was supported in part by JSPS KAKENHI, Grants 19H02155 and 21H03427, JST PRESTO JPMJPR1873, and JST COI JPMJCE1307. We thank Richard Haase, Ph.D, from Edanz Group (https://en-author-services.edanz.com/ac) for editing a draft of this manuscript.

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