Comparison of New Decoding Based on Correlation or Convolution between Hadamard- and Golay-Coded Ultrasonic Array Transmissions

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1. Introduction

For high-frame-rate medical ultrasound-array-beamformed imaging at deeply located tissues such as a heart, a liver, etc., the Hadamard [1] and Golay codes [2] are often used for coding at plane or diverging wave transmission [3], and decoding is performed by solving equations with much computational processing. In our laboratory, we have been proposing 2 new decoding methods with less processing, i.e., (i) correlation and (ii) convolution [4]. In this report, we confirmed the feasibilities of the 2 methods and compared the 2 codes through simulations.

2. Methods

2.1 Correlation and Convolution

For decoding, the correlation (i.e., matched filter, inner product) was performed with the transmitted waves or the codes themselves. Convolution (i.e., filtering) was also performed instead. In practice, the use of codes themselves is more useful than that of transmitted waves. The longer the code length, the faster it is to achieve the decoding in the frequency domain rather than in the spatial domain. Here, the impulse response of the ultrasonic probe element was set to an ideal one wave, or for practical two to four waves.

2.2 One- and Half-Period Wave Coding

In general, a code is assigned to every one-period wave. However, in this report, to increase the spatial resolutions in depth and lateral directions, we also assigned a code to every half-period wave instead.

2.3 Apodization

The method described in Section 2.2 improved the spatial resolution but weakened the signal intensity. Then, as an alternative approach, we also used the Chebyshev window for weighting the transmitted waves or the codes. It has been reported that 1/2 power of the apodization is applied in the post-processing for chirp processing [5]. Here, we used the 1/2, 1st and 2nd powers of Chebyshev window.

3. Simulations

3.1 Setup

A linear-array-type probe was used in the simulations (Field II [6]). The nominal frequency was 2.5 MHz, the number of elements was 64, the element width was 0.30 mm, and the kerf was 0.06 mm. Point scatterers were placed at depths of 10, 60, 110, and 160 mm at the center of the array. The respective Hadamard- and Golay-coded plane waves were transmitted, of which code lengths were set to same 64. Regardless the dynamic focal depth, the effective synthetic aperture (SA) widths for the decoded rf-signals were fixed at 64 elements.

3.2 Results

Figs. 1a to 1c respectively show for depths of 10, 60 and 110 mm the gray-scaled synthetic aperture images, of which left and right figures are obtained through the correlation and the convolution processing with transmitted waves, for instance, when the impulse response was one-period wave and the Hadamard code was used. Due to such sever artifacts shown, it is difficult to argue the superiority or inferiority of Hadamard and Golay codes particularly when the impulse response is long (figures omitted), and it is necessary to discuss the results statistically. **Figs. 2** and **3** respectively show the averaged images obtained through 40-times shuffles of 64 Hadamard and Golay codes. With the more shuffles, the artifacts decreased more efficiently for the Hadamard than for the Golay code (figs omitted). It was suggested that when the target included more reflectors and scatters, the Hadamard code was more effective than the Golay code. The decoding with codes themselves generated almost the same images, but with slightly more artifacts (figs omitted).

As expected, the correlation was more stable with fewer artifacts than the filtering. The longer impulse response gave the higher signal intensity at depth, but it produced false images and reduced the spatial resolution in the depth direction (figs omitted), making the one-period wave better. Interestingly enough, the lateral spatial resolution became higher inversely. At all depths, both in correlation and filtering, Hadamard had a smaller false image than Golay, and especially when filtering, Golay did not form images well at depth.

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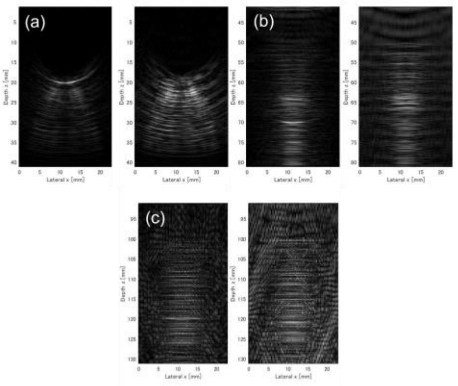

Fig. 1. Hadamard with 1-period wave impulse response.

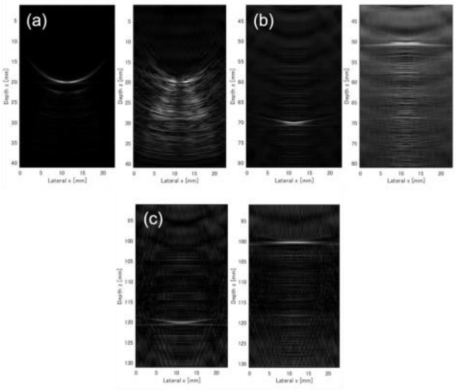

Fig. 2. Hadamard with 40 shuffle codes.

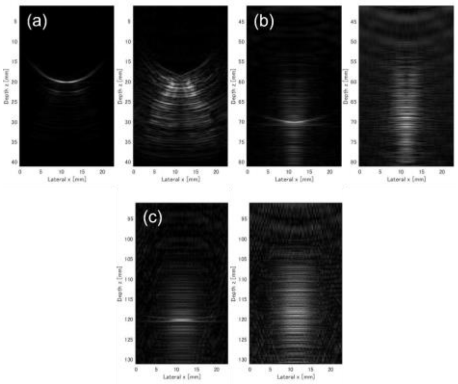

Fig. 3. Golay with 40 shuffle codes.

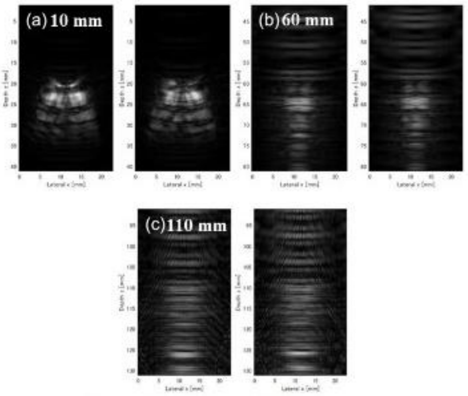

Fig. 4. Squared apodization for Hadamard (no shuffle).

In terms of resolution, Hadamard and Golay were better in depth and lateral directions, respectively.

The half-wave encoding gave better spatial resolutions in both depth and lateral directions and the images obtained with the correlation and filtering became similar, but the signal intensity was weaker (figs omitted), confirming that a longer impulse response will be better depending on a system noise contamination. However, within the simulations, the every one-wave encoding was more stable.

The apodization decreased artifacts and improved both the spatial resolutions, but was effective at a shallow location regardless the impulse response length and at a deep location only with a long impulse response (figs omitted). The images obtained with the correlation and filtering also became similar. Higher power orders were more effective. **Fig. 4** shows the 2nd power weighting results for Hadamard with 4-wave impulse response (no shuffled ones).

4. Discussions and Conclusions

The proposed correlation and filtering methods produced images at depth in the simulations with sparse scatters, but as mentioned above, the correlation method was more effective. Overall, the Hadamard code was more effective than Golay code. The reason is that the transmission wave shapes and codes with Hadamard are more regular than those of Golay. At the presentation or in a paper, a target having dense reflectors or scatters, or more shuffles (omitted ones) will also be dealt with.

For real-world applications, a tissue ultrasound attenuation should also be considered with the coding. However, for practical echoic human in vivo tissues, high SNR echoes will be generated even for deeply situated tissues such as a heart or a liver, etc. The more effective code are also being investigated now. The proposed methods are significantly fast and can be expected to be more useful than equation solving. We will also perform lateral apodization transmission/reception and conduct experiments.

References

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