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Singular value decomposition of element echo signal received by individual elements for clutter reduction

クラッタ除去のための超音波素子信号の特異値分解

Michiya Mozumi†, Ryo Nagaoka and Hideyuki Hasegawa
([1]Graduate School of Science and Engineering for Research, University of Toyama)
茂澄倫也†，長岡　亮，長谷川英之　（富山大院 理工）

1. Introduction

Visualization of intracardiac blood flow helps us to evaluate pumping function of human heart[1]. In the cardiac lumen, there is a complex blood flow dynamics such as vortex flow[1,2], and the high frame-rate imaging is suitable for visualization of such complex blood flow. Ultrasound imaging with parallel receive beamforming can achieve a higher frame rate of several kHz[3-5].

Because an amplitude of tissue signals is typically 60 dB higher than that of blood signals, a clutter filter, which is a signal processing technique for reduction of the tissue signal, is needed to enhance the blood signal. High-pass filtering in the frame direction applied to ultrasound received signals at a specific position is commonly used for suppression of such clutters. Recently, singular value decomposition (SVD) filtering gains attention, and the SVD filtering was applied to diagnostic modalities such as magnetic resonance imaging (MRI)[6] and x-ray computer tomography (CT)[7]. In the field of ultrasound imaging, the SVD filtering has also been studied for the purpose of clutter reduction[8,9], and the SVD-based clutter filter seems to outperform conventional high-pass filtering methods which are based on finite-length impulse response (FIR) filter and infinite-length impulse response (IIR) filter[10]. However, the applications are limited to the blood flow near the surface or that with slower velocities.

To extract the signal of the intracardiac blood flow, the SVD clutter filtering is applied to ultrasound echo signals of human heart. In previous studies, A data matrix, which was prepared to be decomposed into each signal components, was typically composed of beamformed RF signals. In this study, we applied the SVD filtering to RF echo signals received by individual array elements for the purpose of clutter reduction.

2. Materials and Methods

2.1 SVD filtering

Let us define echo signals received by individual transducer elements $s(x,z,t)$. A spatiotemporal matrix $\mathbf{S}$ is created by rearranging echo data $s(x,z,t)$; (n_x, n_z, n_t) to the Casorati matrix of size $(n_x \times n_z, n_t)$, where n_x, n_z, and n_t represent the number of sampling points corresponding to the lateral, depth, and frame direction, respectively. The spatiotemporal matrix $\mathbf{S}$ is decomposed into a product of three matrices by the SVD as

$$\mathbf{S} = \mathbf{U} \cdot \mathbf{\Sigma} \cdot \mathbf{V}^{\mathrm{T}}, \tag{1}$$

where $\mathbf{U}$ and $\mathbf{V}$ are matrices consisting of spatial and temporal singular vectors, respectively. Superscript $\cdot^{\mathrm{T}}$ represents transpose, and $\mathbf{\Sigma}$ is diagonal matrix composed of singular values arranged in a descending order. The SVD filtering is performed by substituting $\mathbf{\Sigma}$ as

$$\mathbf{S}^{\mathrm{f}} = \mathbf{U} \cdot \mathbf{\Sigma}^{\mathrm{f}} \cdot \mathbf{V}^{\mathrm{T}}, \tag{2}$$

where $\mathbf{S}^{\mathrm{f}}$ is a matrix composed of filtered element echo signals, and $\mathbf{\Sigma}^{\mathrm{f}}$ is a diagonal matrix which is obtained by replacing several largest singular values of $\mathbf{\Sigma}$ with zero. Singular values correspond to an energy of the singular vectors. From this viewpoint, the low-order singular components are assumed to be related to the clutter signals, and thus, clutter reduction is accomplished by removing the low-order singular components as shown in Eq. (2).

Similarly, high-order singular components are assumed to be related to noise components because the energy of noise signals is much lower than that of the blood signals, and the noise suppression can be also achieved by replacing several smallest singular values of $\mathbf{\Sigma}$ with zero. In this study, threshold values of SVD clutter filtering were chosen manually.

2.2 Experimental setup and image reconstruction

The transmit-receive sequence is described in Ref. 11. A phased array probe at a nominal center frequency of 3 MHz was used. To create one B-mode image, one spherical wave was transmitted to illuminate a wider region, and ultrasound echo signals received by individual transducer elements were obtained at a sampling frequency of 31.25 MHz. For reduction of clutter components in ultrasound echo signals, the SVD clutter filtering was applied to the ultrasound echo signals received by individual transducer elements. After this, the filtered element echo signals were beamformed and 241 receiving beams were created simultaneously.

E-mail: hasegawa@eng.u-toyama.ac.jp

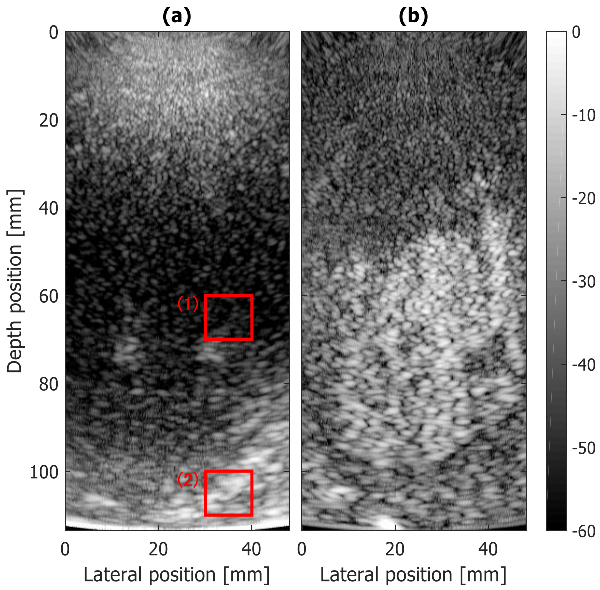

Fig. 1 B-mode image of left ventricular wall in diastolic phase. (a) Original beamformed signals. (b) Filtered signals from intracardiac blood flow obtained with SVD clutter filter. Regions of interest (ROI) #1 and #2 represent pixels of cardiac lumen and heart wall, respectively.

Although a phased array probe was used to transmission of a diverging spherical wave, receiving focal points were aligned in the Cartesian coordinate to avoid a redundant effect due to non-constant sampling interval in the polar coordinate[11]. As a result, a frame rate of 6250 Hz was archived through such a transmit-receive sequence. Beamformed RF signals were weighted by the coherence factor, which can be calculated from the delay-compensated echo signals received by individual transducer elements in order to improve the lateral resolution and suppress side lobes[12,13].

3. Experimental Results

The filtered B-mode image was compared with the original B-mode image. **Figure 1(a)** shows a B-mode image of a human heart. Red squares #1 and #2 shown in Fig. 1(a) show regions of interest (ROI) corresponding to cardiac lumen and heart wall, respectively. In **Fig. 1**, the only heart walls were visualized, and the left ventricular hemodynamics could not be observed. **Figure** 1(b) shows a B-mode image of intracardiac blood flow obtained by the SVD clutter filtering. By applying the SVD clutter filter, the clutter signals from the heart wall was suppressed, and the blood signals flowing in cardiac lumen could be visualized.

E-mail: hasegawa@eng.u-toyama.ac.jp

To evaluate the performance of the proposed method, ratios of echo amplitudes in ROIs #1 to #2 were calculated using B-mode images shown in **Figs. 1(a) and 1(b)**. The results in **Figs. 1(a) and 1(b)** are -34.6 and 12.3 dB, respectively. This result showed that the proposed SVD filter suppressed the clutter signals and emphasized the signals from the blood flow in cardiac lumen.

4. Conclusion

In this study, we applied the SVD clutter filter to the ultrasound echo signals received by individual transducer elements. The experimental results indicated that the proposed filter suppressed the clutter signals from left ventricular wall, and extracted the signals from intracardiac blood. As further researches, we will compare the proposed SVD filter with the conventional clutter filtering method to evaluate the performance of the proposed filter.

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