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Singular Value Decomposition of Ultrasound Signals for Tissue Boundary Detection in M-mode

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1. Introduction

Ultrasound is a popular method to measure internal tissue motion. For continuous and long-term monitoring, traditional handheld clinical probes may impose a challenge as they may impede the motion of the underlying tissue of interest due to their size and weight, and could also cause motion artifacts. One may use a lightweight, flexible, and wearable ultrasound sensor (WUS) to address this challenge[1,2]. Unlike focused ultrasound beam featured in clinical probes, the WUS employs non-focused ultrasound, which often results in weaker reflected boundary echoes and more speckle noises from surrounding tissues in acquired ultrasound radiofrequency (RF) signals when the size of a tissue boundary of interest is smaller than the ultrasound beam. Thus, the acquired RF signals may have a lower signal-to-noise ratio (SNR).

Relative change in tissue boundary location can be estimated from the phase information of ultrasound RF signals by quadrature demodulation techniques[3], but the initial depth location of the boundary needs to be determined by other techniques. Singular value decomposition (SVD) has been proposed as a method to separate target structure from speckle noise in B-mode[4,5], and has also been demonstrated to separate tissue, blood-flow and cavitation signals based on spatio-temporal characteristics[6]. In this paper the use of singular values (SV) is proposed to identify artery boundary with WUS using the pulse echo technique in M-mode.

2. Methodology for SVD-Based Boundary Detection

Amplitude matrix of ultrasound RF signals acquired in M-mode measurement is defined as $\mathbf{S} = S(z,t)$, where z is the discrete sampled depth ($z = 1, \ldots, Z$) and t is the discrete sampled measurement time ($t = 1, \ldots, T$), and Z and T are the size of the M-mode image, respectively, as shown in **Fig. 1.** The sub-matrix $\mathbf{S}_{KL}(z,t)$ is defined as a subcomponent of $\mathbf{S}$ in a kernel of size $K \times L$ centered at (z,t). The SVD is applied to $\mathbf{S}_{KL}(z,t)$ to get

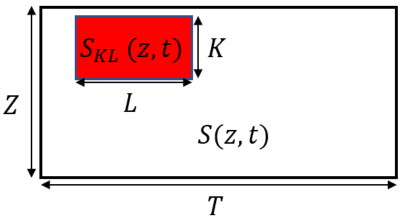

Fig. 1 Schematic of subcomponent of ultrasound RF signals used for the proposed SVD boundary detection.

$$\mathbf{S}_{KL}(z,t) = \boldsymbol{U}_{z,t}\boldsymbol{\Sigma}_{z,t}\boldsymbol{V}^{*}_{z,t} \tag{1}$$

where $\boldsymbol{U}_{z,t}$ is a $K \times K$ unitary matrix, $\boldsymbol{\Sigma}_{z,t}$ is a $K \times L$ diagonal matrix, and $\boldsymbol{V}_{z,t}$ is a $L \times L$ unitary Matrix, and * represents matrix transposition. The diagonals of $\boldsymbol{\Sigma}_{z,t}$ contain the singular values (SV) $\sigma_{i,z,t}$, where i is the SV index. Let $\sigma_{it}(z) = \{\sigma_{i,z,t}, z \in \mathbb{Z}, z = 1, \ldots, Z\}$ be defined as the set of the i^{th} SV calculated at each z of (1) at a given time index t. The location of the boundary $\hat{z}_{i,t}$ at the given time index t is determined by the maximum value of the i^{th} SV by:

$$\hat{z}_{i,t} = \operatorname{argmax}_{z}\left(\sigma_{it}(z)\right) \tag{2}$$

In this paper, the use of $i = 1$ and $i = 2$ for boundary detection is investigated. The results of SV value at $i = 1$ and $i = 2$ are referred as SV-1 and SV-2, respectively. The sizes K and L of the subcomponent $\mathbf{S}_{KL}(z,t)$ influence the spatial resolution and temporal smoothness of the boundary detection, respectively. In this study, K is determined to be one wavelength of the transmitted ultrasound pulse while L is set such that it corresponds to 0.01s.

3. In-vivo Experiment at Brachial Artery

3.1 Experimental Procedure

The WUS was attached to a healthy subject's left forearm above the brachial artery with an ultrasonic couplant gel. Ultrasonic pulse echo measurements were performed for 5s with a frame rate of 1 kHz and a sampling rate of 125 MHz, in order to measure the motion of the brachial artery boundary due to the heartbeat at rest. The details of the WUS and measurement configuration were reported previously [2].

3.2 Results and Discussion

The M-mode image of the acquired ultrasound RF signals around the anterior boundary of the brachial artery is shown in **Fig. 2**. To determine a reference motion for the anterior boundary, quadrature detection technique[3] was applied at the manually selected initial artery boundary location. The result of the boundary motion is given by the solid red line in Fig. 2. The SV values obtained for SV-1 and SV-2 are shown in **Fig. 3a** and **Fig. 3b** respectively. From visual comparison between Fig. 2 and Fig. 3a, the SV-1 values are related to the RF signal amplitude values. The SV-2 values shown in Fig. 3b demonstrates that the value of SV-2 peaks at the locations where the boundaries are moving rapidly from diastolic to systolic state. Therefore, it may be inferred that SV-2 utilizes boundary motion velocity to select the boundary location.

The difference (error) between the determined boundary and reference boundary locations with respect to the motion velocity is shown in **Fig. 4**, where the results by the SV-1 and SV-2 are denoted with the blue cross and red circle marks, respectively. The boundary motion velocity was obtained by taking the absolute value of the derivative of the reference boundary motion in Fig. 2. The errors in SV-2 were smaller than those in SV-1 when the motion velocity was faster than approximately 0.75 mm/s. This result suggests that SV-2 may offer superior performance compared to the SV-1 at the motion velocities faster than 0.75mm/s in the experimental conditions and ultrasound signal analysis employed in this study.

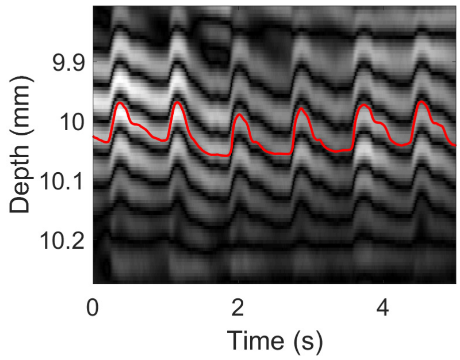

Fig. 2 M-mode image of ultrasound RF signals obtained with WUS and reference boundary motion (red line) estimated by quadrature detection technique.

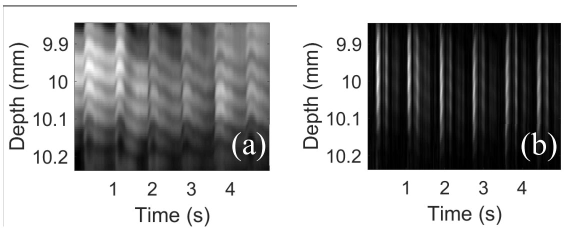

Fig. 3 Values of SV-1 (a) and SV-2 (b) obtained for each (z, t) of ultrasound RF signals shown in Fig. 2.

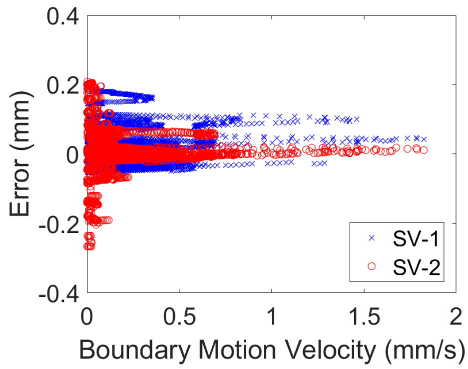

Fig. 4 Errors in boundary location estimation using SV-1 (cross) and SV-2 (circle).

4. Conclusion

A WUS could be used for continuous and long-time monitoring of arterial health and/or cardiac activities. The proposed SVD technique was investigated to identify the initial location of artery boundary. Based on in-vivo experiments and results, it was suggested that the use of the SV-2 may provide a motion-based method to identify the initial location of the arterial boundary.

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References
1. I. AlMohimeed, H. Turkistani, and Y. Ono: Proc. IEEE Int. Ultrason. Symp. (2013) 1137.
2. A. Huang, M. Yoshida, Y. Ono, and S. Rajan: Proc. IEEE Int. Ultrason. Symp., (2017) 1.
3. N. Feng, J. Zhang, and W. Wang: Ultrason. **44**, (2006) e47.
4. H. Hasegawa and R. Nagoaka: Jpn. J. Appl. Phys. **58** (2019) SGGE06.
5. A.C. Yu and L. Lovestakken: IEEE Trans. Ultrason., Ferroelectr., Freq. Control **57** (2010) 1096.
6. H. Ikeda et. al: Jpn. J. Appl. Phys. **57** (2018) 07LF04.