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Cortical Bone Fracture Imaging using Velocity Model Based Multistatic Synthetic Aperture Ultrasound

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***Abstract*—Compared with X-ray tomography, the use of ultrasound provides the advantages of non-ionizing radiation and low cost. However, ultrasound imaging of cortical bone fracture is still challenging due to the significant velocity changes on the interface between the cortical bone (2800-4000 m/s) and soft tissue (1400-1700 m/s). Furthermore, the low contrast-to-noise ratio (CNR) caused by artifact affects the image quality. In this study, we apply a compressed sensing (CS) based three-layer velocity model for cortical bone fracture imaging. Multistatic synthetic aperture ultrasound (MSAU) was utilized to restrain the artifact and provide a high CNR. Synthetic aperture focusing technique (SAFT) was utilized as a comparison of MSAU. *In vitro* experiment was performed to validate the proposed method.**

Keywords—multistatic synthetic aperture ultrasound, cortical bone fracture imaging, compressed sensing, velocity model

I. Introduction

Osteoporotic fracture is related with bone mass loss and bone tissue deterioration [1]. With the aging of the population, osteoporosis affects almost 70 million Chinese over the age of 50, bringing huge financial and medical burden to the society [2]. Therefore, osteoporosis related fracture diagnosis and treatment is of vital importance.

Conventional method, such as X-ray tomography, is the golden standard of fracture diagnosis. In recent years, researchers have explored the application of ultrasound in bone fracture evaluation, which has been proved to be useful in the measurements of bone mineral density [3]. Ultrasonic guided waves has been applied to assess the porosity, thickness and phase velocity of cortical bone, which are the important features for determining cortical bone mechanical properties [4-5]. Ultrasound axial transmission has been used to detect the arrival time and signal amplitude in different fracture geometries [6]. Protopappas *et al.* have applied ultrasonic guided waves in the evaluation of fracture healing with 2-D and 3-D model [7-8]. Xu *et al.* have investigated the feasibility of ultrasonic guided-mode conversion in cortical bone fracture detection through simulation and experiment [9-10]. Ultrasound radiation force have been applied in the assessment of bone fracture healing in children [11]. However, there are two main challenges for ultrasound imaging of cortical bone fracture. First, the velocity changes severely when wave propagates between cortical bone and soft tissue. Second, artifact caused by the strong reflection of cortical bone result in low CNR and low image quality.

To reconstruct the cortical bone fracture image with different velocity, several methods have been applied, such as the split-step Fourier imaging method [12], the Born-based inversion technique [13], and the ray-tracing method [14].

Synthetic aperture technique was originally used in radar system, and it was not applied in ultrasound until the late 1960s [15]. Recently, synthetic aperture ultrasound has been widely used in medical ultrasound imaging, such as breast imaging [16], liver tumor detection [17] and blood velocity estimation [18], since it can improve lateral resolution. However, not enough study has been done on the synthetic aperture ultrasound imaging of cortical bone.

The motivation of the present study is to develop a cortical bone fracture ultrasound imaging method. In this study, we applied a three-layer velocity model for cortical bone fracture imaging, and phase shift migration method was used for image reconstruction. MSAU was utilized to provide high resolution and at the same time restrain the artifact, providing high CNR. The experiment was conducted with a 128-element linear array. SAFT with monostatic acquisition is performed as a comparison of MSAU.

II. Materials & Methods

A. Experiment Set up

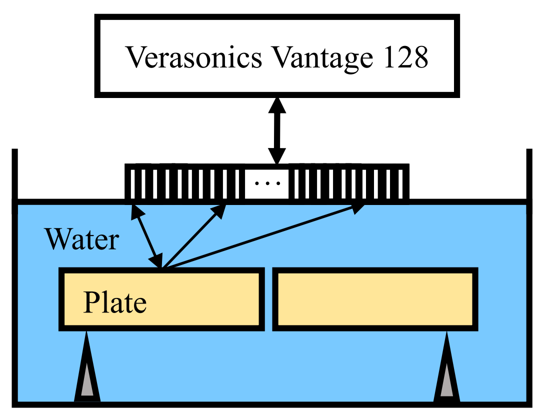

Fig. 1 Experiment set up

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As shown in Fig. 1, water immersed experiment is conducted with a 3.4 mm-thickness fractured bovine plate. The fracture is manually broken with a width of 0.5 to 1.0 mm. The experiment is performed on a multichannel platform (Vantage-128, Verasonics, WA, USA), using a 128-element linear array. The space between elements is 0.3 mm. The emit pulse is a Gaussian envelope sinusoid wave with 6.25 MHz center frequency, and sampling frequency is 25 MHz. The full-matrix dataset is obtained by MSAU with one element transmitting a spherical wave in sequence and all elements receiving. SAFT is also performed as a face-to-face comparison study on the same experiment platform.

B. *Compressed sensing for delay parameter estimation*

CS is applied to extract the delay parameters of the full-matrix dataset. The received signal S can be regarded as the composition of excitation pulse with varying time-delay and weight. A series of excitation pulses X were built with different delays, which are used as the CS bases

$$S = XW \tag{1}$$

where W is the weight obtained by projecting the received signals into the bases.

First, CS is applied to estimate the delay between each receive channel. Then the full-matrix dataset is re-arranged into the zero-offset format based on the delay parameters. Second, CS is applied to estimate the time-delay between the interfaces of the zero-offset data by extracting the bases corresponded with the interface reflected signals.

C. *Vecolicty model and Image reconstruction*

The water immersed bovine plate can be modeled as a water-cortical bone-water structure, and the corresponding velocity model is a three-layer model. With the known velocity of water and cortical bone, and the estimated time-delay between the interfaces, the thickness of each layer can be calculated, thus building the velocity model.

Based on the zero-offset data and velocity model, the image is reconstructed using phase shift migration method in Fourier domain. The flow chart of the proposed method is shown in Fig. 2.

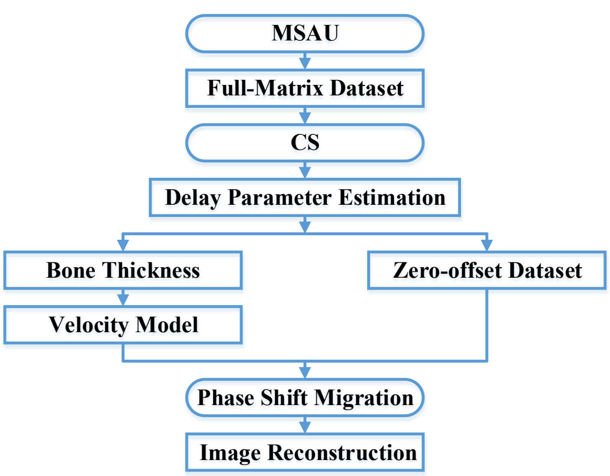

Fig. 2 The flow chart of the proposed method.

III. RESULTS

The received signals of the first 40 channels are presented in Fig. 3. The first and second reflected signals represent the up and bottom layers of bovine plate. Fig. 3(a) shows that there is time-delay between each received signal. Fig. 3(b) shows that there is no time-delay after CS adjustment, indicating that CS can estimate the delay parameters accurately.

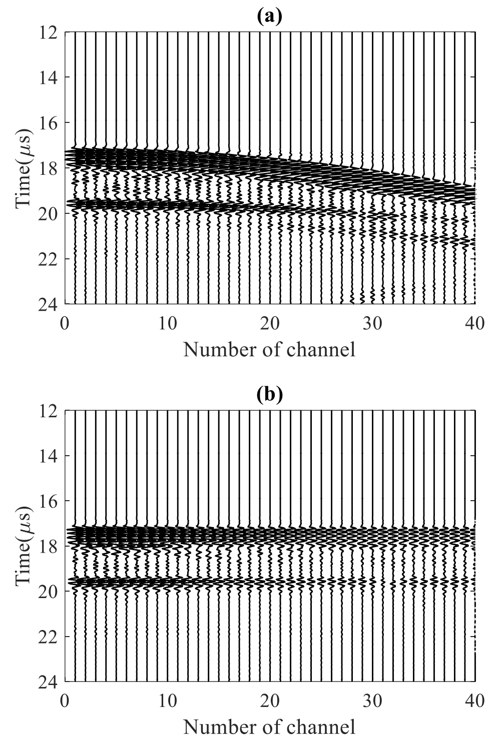

Fig. 3 The received signals of the first 40 channels, (a) the origin signals; (b) the CS adjusted signals.

The reconstructed image using SAFT is shown in Figure. 4(a). The estimated bone thickness is 3.6 mm with a relative error of 5.88% and the CNR is 3.0 dB. Figure. 4(b) illustrates the reconstructed image using MSAU. The estimated bone thickness is 3.5 mm with a relative error of 2.94% and the CNR is 4.9 dB. Compared with SAFT, MSAU shows a better performance on artifact restrain and CNR improvement, and presents the fracture on the diaphyseal shaft clearly.

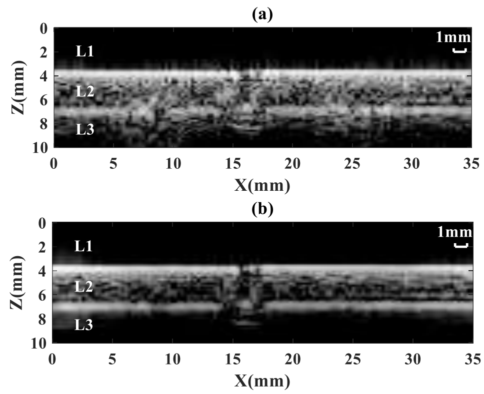

Fig. 4 Experiment results, (a) reconstructed image using SAFT; (b) reconstructed image using MSAU. L1, L2, and L3 indicate the three layers, water, cortical bone, water, respectively.

IV. DISCUSSION

CS was used to estimate the delay parameters. The velocity model was used to cope with the significant velocity change between cortical bone and soft-tissue. MSAU was applied to provide high resolution and CNR, while SAFT was applied as a face to face comparison of MSAU.

The experiment results indicate that CS can estimate the delay parameter accurately, adjusting the full-matrix data into the zero-offset format. The estimated bone thickness of MSAU is 3.5 mm with a relative error of 2.94%, while that of SAFT is 3.6 mm with a relative error of 5.88%. In addition, MSAU shows a better performance on artifact restrain, and improve the CNR from 3.0 dB to 4.9 dB compared with SAFT. However, the experiment is preliminary, the feasibility of the proposed method should be further tested on irregular cortical bone, and *in vivo* experiment should also be investigated.

V. CONCLUSION

In this study, a multistatic synthetic aperture ultrasound imaging of cortical bone fracture using velocity model is presented. It is shown that CS is useful in delay parameter estimation. With the known velocity and delay parameter, the width of each layer can be estimated, thus building an accurate velocity model. Compared with SAFT, the application of MSAU can restrain the artifact and improve the CNR of the reconstructed image. The proposed method could be applied in the cortical bone fracture ultrasound imaging.

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