2D Complex Shear Modulus Imaging in Gaussian Noise

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Table of Contents

2D Complex Shear Modulus Imaging in Gaussian Noise

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Abstract— **Dynamic shear-wave estimation of complex shear modulus (CSM) has demonstrated the ability to detect tumors. Ultrasound shear wave imaging is one of the methods for quantitatively estimating relevant elasticity parameters of tissues via the wave number and propagation attenuation of ultrasound waves. Maximum Likelihood Ensemble Filter (MLEF) has been efficiently applied for estimating the CSM parameters, but limited to one-dimensional (1D) scenario. This paper extends this method to detecting two-dimensional (2D) objects affected by Gaussian noise during the Doppler acquisition. A ray scanning method is used for modeling the propagation directions (lines) along each of which the MLEF is used for estimating the CSM parameters. The object 2D image is then reconstructed by transforming these estimated CSM parameters from the polar coordinates to Cartesian coordinates. it is not necessary to increase the ensemble size (which means an increase in the algorithm complexity) when the noise level is low.**

Keywords— **Ultrasound shear wave imaging, maximum likelihood ensemble filter (MLEF), complex shear modulus (CSM), elasticity imaging.**

I. INTRODUCTION

Many pathological processes in tissues are recognized by morphological changes that reflect alterations of mechanical properties of soft tissues. Among various elasticity imaging modalities, ultrasonic shear wave imaging technique has been developed for estimating the complex shear modulus (CSM) of biphasic hydro polymers including soft biological tissues. Shear wave imaging has the potential to bridge molecular, cellular and tissue biology, and to support medical diagnoses and patient treatment.

In 2004, Chen et al. found that the propagation speed of shear waves is related to the frequency, the elasticity and viscosity of the medium [1]. Hence, they proposed a method to estimate shear elasticity and viscosity of a homogeneous medium by measuring the shear wave speed dispersion. In 2009, Orescanin et al. applied the Kelvin–Voigt model to estimate the CSM of the liver for shear wave frequencies between 50 and 300 Hz [2]. Then, the Maximum Likelihood Ensemble Filter (MLEF) was applied for CSM estimation for homogeneous medium [3, 4]. It was extended to 1D heterogeneous medium in [5]. In this paper, we extended this method to detecting two-dimensional objects[1]. In addition, we study the effect of Gaussian noise corrupting the Doppler acquisition in conjunction with the effect of the ensemble size of the MLEF.

II. MATERIALS AND METHODS

First, a needle vibrating with the frequency of f(Hz) is used for creating a shear wave whose velocities will then be measured by a Doppler scanner [6]. Second, a ray scanning method is used for modeling the propagation directions. Denote $\alpha(r)$ and $k_s(r)$ the shear wave attenuation coefficient and the wave number at the tracking location r along each ray; r is defined in the polar coordinates as: $r = \rho e^{j\theta}$. Third, the CSM of the tissue located at r is then estimated from $\alpha(r)$ and $k_s(r)$, which are the real and imaginary parts of the CSM value, based on using the Kelvin-Voigt model for a viscous medium [3]. Last, the 2D image of the object is reconstructed by transforming these estimated CSM parameters from the polar coordinates to Cartesian coordinates.

A. Shear Wave Propagation

The needle vibrates along the vertical (z) axis. Under an assumption of cylindrical shear wave propagation along the radial axis, the particle velocity of ray i is a spatio-temporal function of the radial distance r and time t, and is given by

$$v^i(r,t) = \frac{1}{\sqrt{r}} A e^{-\alpha(r) r} \cos(\omega t - k_s(r) r),\ i = 1, \dots, L \qquad (1)$$

where L is number of ray, A is the magnitude of the wave at the source location, ω is the angular shear frequency. In discrete form, we have

$$v^i{}_n = \frac{1}{\sqrt{r - r_0}} A e^{-\alpha(r)(r - r_0)} \cos(\omega n \Delta t - k_s(r)(r - r_0) - \phi), \qquad (2)$$

where index n denotes the discrete time, r_0 is the initial distance from the source, Δt is discrete-time step and ϕ represents the initial temporal phase.

Eq. (2) can be rewritten in a recursive form by:

[1] Part of this study was presented in the 2013 International Conference on Green and Human Information Technology (ICGHIT 2013) as an in-progress work.

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$$v^{i}{}_{n}(r) = v^{i}{}_{n-1}\cos(\omega\Delta t) - \frac{1}{\sqrt{r-r_0}} A e^{-\alpha(r-r_0)} \times \sin(\omega(n-1)\Delta t - k_s(r-r_0) - \phi)\sin(\omega\Delta t). \quad (3a)$$

Given the effect of Gaussian noise $w^{i}{}_{n}(r)$ on the velocity at each spatial location, we have the following model:

$$v^{i}{}_{n}(r) := v^{i}{}_{n}(r) + w^{i}{}_{n}(r). \quad (3b)$$

B. Attenuation Coefficient and Wave Number Estimation

In this subsection, we apply the MLEF to estimate k_s and α in each ray. The state equation can be constructed from Eq. (3a)as shown below:

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{v}_n \\ \boldsymbol{\theta}_n \end{bmatrix} = \begin{bmatrix} \mathcal{F}(\boldsymbol{v}_{n-1}, \boldsymbol{\theta}_{n-1}) \\ \boldsymbol{\theta}_{n-1} \end{bmatrix} \quad (4)$$

where $\boldsymbol{\theta}_n = [\boldsymbol{\alpha}^T, \mathbf{k}_s^T, \phi, r, A]^T$, $\mathcal{F}$is a nonlinear function modeling the spatial shear wave dynamics. The length of vectors$\mathbf{v}_n$,$\boldsymbol{\alpha}$ and $\mathbf{k}_s$equals to the number of spatial locations. We can assume that $\boldsymbol{\theta}_n$would not be changed during the time of the experiment; hence, $\boldsymbol{\theta}_n = \boldsymbol{\theta}_{n-1}$as shown in Eq. (4).

By using the Doppler acquisition, the measurements of velocities at every spatial locations are given by

$$\boldsymbol{y}_n = \begin{bmatrix} \widehat{\boldsymbol{v}}_n \\ \mathbf{0} \end{bmatrix} = [\boldsymbol{I} \quad \boldsymbol{O}] \begin{bmatrix} \boldsymbol{v}_n \\ \boldsymbol{\theta}_n \end{bmatrix} + \begin{bmatrix} \boldsymbol{W} \\ 0 \end{bmatrix}, \quad (5)$$

where $\mathbf{w}$ is the measurement noise vector.
From Eqs. (4) and (5), the shear wave attenuation coefficient $\alpha(r)$ and the wave number $k_s(r)$ of each ray are estimated by using MLEF according to the algorithm in [4].

C. CSM Estimation Using Kelvin-Voigt Rheological Model

We apply the Kelvin-Voigt model, as illustrated in Fig.1, to estimate the CSM. For a viscous elastic medium, the CSM μ is modeled by an elastic component μ_1 in parallel with the dynamic viscous component η as:

$$\boldsymbol{\mu} = \overline{\boldsymbol{\mu}} - \boldsymbol{i\omega\eta}, \quad (6)$$

The complex wave number for a viscous medium is given by

$$k'_s = \sqrt{\rho\omega^2/\mu}. \quad (7)$$

Since k'_s is complex, it can be written as

$$k'_s = k_s - i\alpha., \quad (8)$$

From (7) and (8), by estimating k_s and α, we can obtain μ.

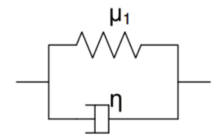


Fig. 1 Diagram of Kelvin-Voigt model

D. Detecting the Presence of 2 D Object

In this work, we verify the proposed method using a two-object simulation scenario. Each object was 'placed' at a certain spatial location $r = \rho e^{j\theta}$. We use a "ray scanning" method to cover the area of interest, in steps of a constant angle (see Fig. 2). The whole area is scanned by varying θ from 0° to 90° in step of 1°, creating 90 rays of interest. Given the availability of 43 elements in the in-use Doppler scanner, we select 43 evenly-spaced spatial locations r along each ray. After collecting all information of these 90 rays, we estimated $\alpha(r)$ and $k_s(r)$. For a given CSM value μ corresponding to a particular material of an object under interest, we establish a detection threshold pair of (α^*, k_s^*) such that the object is detected to be present if the following conditions: $\alpha(r) > \alpha^*$ and $k_s(r) < k_s^*$ for all r. In this paper, the value of the threshold pair can be found empirically via numerical simulation.

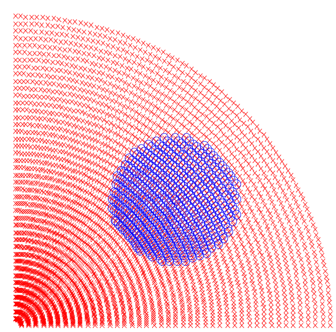


Fig. 2 Ray scanning illustration

III. NUMERICAL RESULTS AND DISCUSSIONS

In this study, we examine the proposed method for detecting 2 circular objects whose elasticity properties are different (i.e., the CSM values are different). Object 1 is placed at location (6 mm, 1.4 mm) with the radius of 1.4 mm. Object 2 is placed at (10 mm, 8 mm) with the radius of 3 mm. The CSM values of the two objects are ($\bar{\mu}$ = 900 Pa, η = 0.3 Pa/s) and ($\bar{\mu}$ = 800 Pa, η = 0.2 Pa/s) respectively. Accordingly, we have ($\alpha = 67.5$; $k_s = 651.7$) for Object 1 and ($\alpha = 54.3$; $k_s = 696$) for Object 2. We asssum that the first spatial location, r_0, is close to the needle: r_0 = 0.4 mm.

Base on empirical study, we found that the detection threshold pair for Objects 1 and 2 are ($\alpha^* = 50$; $k_s^* = 670$) and and ($\alpha^* = 44$; $k_s^* = 710$), respectively. The amplitude A and the phase ϕ are estimated using the first cycle of the particle velocity at r_0. These parameters are then used for calculating the initial state vector of the MLEF. The initial error square-root covariance matrix is Gaussianly randomly generated. After only tens of iterations, the velocity is denoised and the attenuation and wave number are estimated. Based on the results obtained from the MLEF, we apply Kelvin – Voigt rheological model to estimate CSM. Finally, we construct the 2D image. The 2D image in Cartesian coordinates of the simulation scenario is shown in Fig. 3.

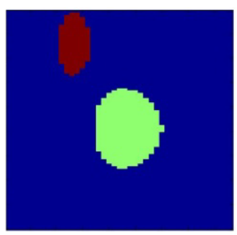


Fig. 3 Original image.

A. In Noise-Free Environment

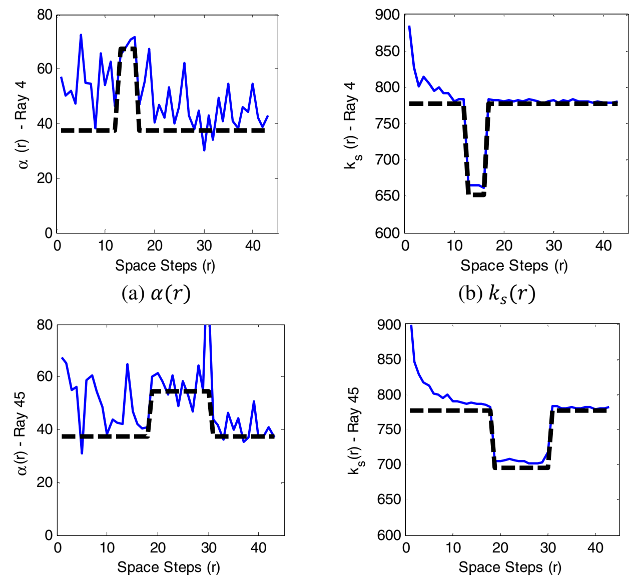
Fig. 4 shows the estimated $\alpha(r)$ and $k_s(r)$ from rays 4 and 45, which are chosenly specifically so that ray 4 passes Object 1 and ray 45 passes Object 2, with no noise effect in the Doppler acquisition. The solid curves are the estimated attenuation and wave number, and the dashed curves are ideal ones. It is show that Object 1 is detected to be present in the interval of $r = [11, 16]$ and Object 2 in that of $r = [18, 30]$. In this study, the MLEF ensemble size is $s = 86$, which is equal to twice the number of elements of the Doppler scanner.

Then, the 2D reconstructed image and their 2D images of attenuation and wave number are shown in Fig. 5. It is obvious that the objects were detected. However, it can be seen that the wave number was better estimated then the attenuation.

B. In Gaussian Environment

Figures 6 to 9 illustrate the effect of Gaussian noise and the MLEF ensemble size on the reconstructed images and their corresponding images of attenuation and wave number, tested for the signal-to-noise ratio (SNR) of 40 and 34 dB and the ensemble size of 43 and 86. With a large value of the ensemble size ($s = 86$), we were able to detect the objects when the Doppler acquisition was corrupted by the noise.

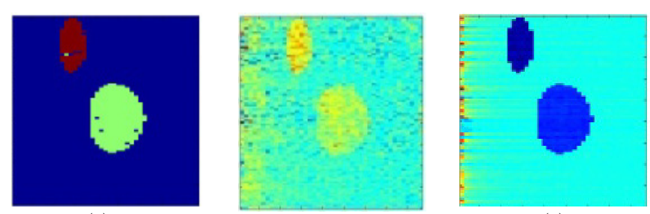
Fig. 10 provides an insight into the effect of the ensemble size on the image reconstruction, measured by the peak-signal-to-noise ratio (PSNR), with respect to different noise levels (SNR = 20 to 40 dB). It can be seen that at a high-level of noise, a higher ensemble size offers a larger PSNR, which means a better quality. However, it is not necessary to increase the ensemble size (which means an increase in the algorithm complexity) when the noise level is low.



(a) $\alpha(r)$ (b) $k_s(r)$

(c) $\alpha(r)$ (d) $k_s(r)$

Fig. 4 $\alpha(r)$ and $k_s(r)$ along ray 4 (top) and ray 45 (bottom); $s = 86$.



(a) (b) (c)

Fig. 5 Reconstructed image (a), Attenuation (b) Wave number (c) images with ensemble size of $s = 86$.

IV. CONCLUSIONS

Based on the MLEF approach, this paper has proposed a ray-tracing based method to estimate the elasticity properties of 2D objects in shear wave imaging. The experiment is quite simple when only a single vibration frequency is needed to accurately estimate the CSM in the medium. Quantitative analysis for different levels of Gaussian noise affecting the Doppler acquisition, the ensemble size were studied. In future work, it is desirable to examine further thoroughly the optimal imaging thresholds pair, $(\alpha^*,\ k_s^*)$, used for detecting the objects under various practical CSM values. In addition, better estimation of the attenuation should be investigated.

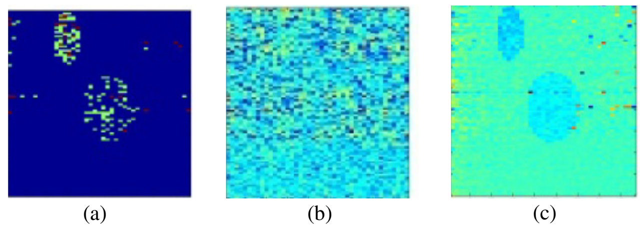


Fig. 6 Reconstructed (a), Attenuation (b), and Wave number images with s = 43, SNR = 40 dB. The obtained PSNR = 10.4.

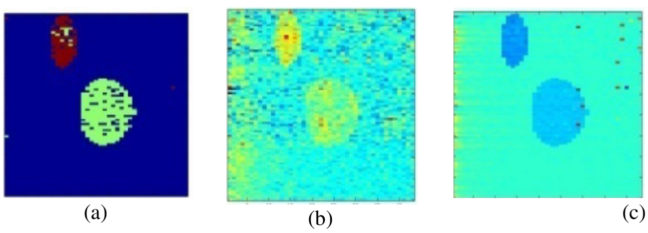


Fig. 7 Reconstructed (a), Shear attenuation (b), and Wave number images with s = 86, SNR = 40dB. The obtained PSNR = 10.31.

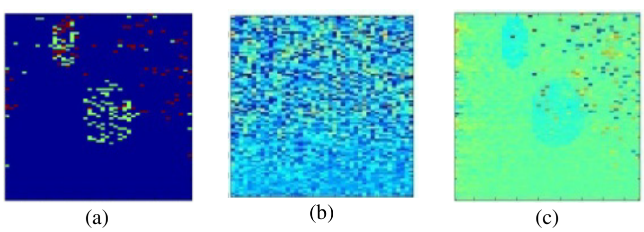


Fig. 8 Reconstructed (a), Shear attenuation (b), and Wave number images with s = 43, SNR = 34 dB. The obtained PSNR = 6.58.

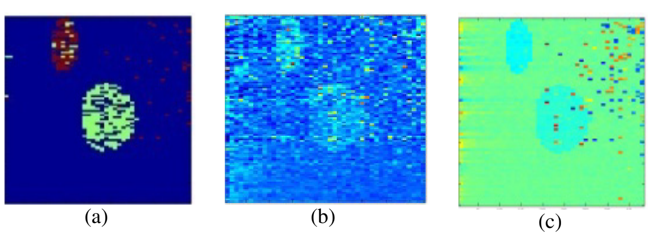


Fig. 9 (a) Reconstructed (a), Shear attenuation (b), and Wave number images with s = 86, SNR = 34 dB. The obtained PSNR = 8.46.

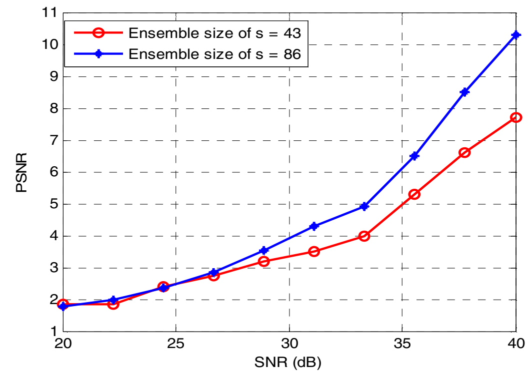


Fig. 10 Effects of noise and ensemble size.

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