Élastographie Passive par Ondes de Cisaillement

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Introduction

Passive tomography based on noise correlation is a recent method for extracting information from a complex wave field. It has been experimentally demonstrated in different fields and specially in geophysics and mantle crust tomography [1] that it is possible to retrieve the Green's functions from the correlation of a noise-like signal between the sensors. A new approach of the shear wave elasticity mapping of soft tissue known as elastography is presented in this study. Called physiological or passive elastography, this new approach aims to replace the active sources (radiation force or mechanical vibrators) generally used to generate shear wave in human organs by their natural activity (heart beating, muscular activity, the pulsatility, etc. …). The feasibility of the passive approach has been demonstrated using an ultrafast ultrasound scanner [2] as well as a conventional ultrasound scanner [3] working at 25 frames per second. In this case we are below the Shannon-Nyquist sampling rate; this means that we have only access to the spatial information of the wave field, therefore we are only able to construct a wavelength tomography. Using an ultrafast ultrasound scanner, we can overcome the under-sampling limit and tack this work a step farther to reconstruct a quantitative shear wave speed tomography. Some quantitative tomography using an ultrafast scanner (Versonics system) and new reconstruction algorithms will be presented in this document.

The experimental setup

Experiments in CIRS® elastography phantom containing four spherical inclusions 5 mm diameter, with different shear elasticity ranging from 8 to 80 KPa were performed (fig.1.top). The high frame rate imaging system is the Verasonics ultrasound scanner (Verasonics V-1, Redmond, WA, USA), with frame rate of 500 fps, connected to a 128 channels probe with 9 MHz central frequency.

The diffuse wave field is created inside the phantom using multiple random mechanical vibrations generated by magnetic shakers. The acquisition last 2 seconds, then using the speckle tracking algorithm, we can measure the 2D local displacement field $\varphi\,(\overrightarrow{r_0},t)$ inside the soft solid (fig.1.bottom) based on the beam-formed RF images.

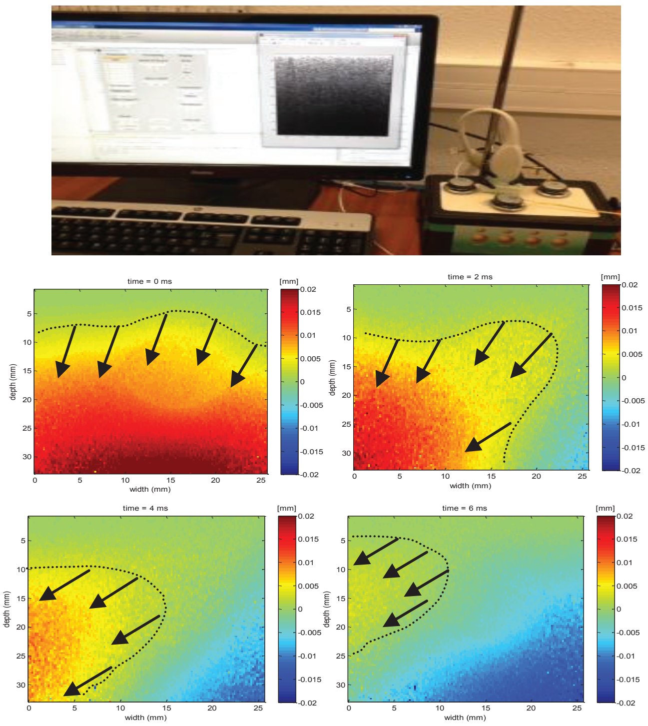

Fig.1. Top: the experiment setup. bottom: An experimental diffuse wave field is represented in these four consecutive snapshots.

The ultrafast imaging allows us to follow continuously the propagation of the diffuse shear wave field. The displacement field measured using the ultrafast scanner (Fig.1.bottom) shows a typical diffuse field, wave front (dashed lines) is propagating and distorted in the direction of arrows.

Shear wave speed tomography

Our inverse problem is based on the physics of the time reversal, which happens to be the same mathematics as the correlation technics. It combines the time derivative of the wave field and its gradient to retrieve the shear wave speed maps. The term of time reversal (TR) will be used to mention the spatio-temporal correlation.

The displacement field $\varphi\,(\overrightarrow{r_0},t)$ can be expressed as a time-convolution product of a source term $s(\overrightarrow{r_s}\,,t)$ located on $\overrightarrow{r_s}$ and the impulse response h between the source and the receiver on point $\overrightarrow{r_0}$

$$\varphi\,(\overrightarrow{r_0},t)\ = s(\overrightarrow{r_s}\,,t) \otimes h\,(\overrightarrow{r_0},\overrightarrow{r_s},t) \tag{1}$$

If we replace the emitted signal by the its time reversed version, and if we spouse that we have a point pulsed source $s(\overrightarrow{r_s}\,,t) = \delta\,(\overrightarrow{r_s}\,,t)$, we can write the time reversal of the wave field $\varphi^{RT}\,(\vec{r},t)$ as following:

$$\varphi^{RT}\,(\vec{r},t) = \varphi\,(\overrightarrow{r_0},-t) \otimes \varphi\,(\vec{r},t) \tag{2}$$

The generalized expression in the eq. (2) can be associated to any wave field that obeys the wave equation. The gradient, i.e. the strain ε_z of the displacement φ field or the time derivative v, i.e. particle velocity of the displacement field φ obeys also to the wave equation. So we can write the time reversal of the strain field and the particle velocity field (eq.3).

$$\begin{cases} v^{RT}(\overrightarrow{r_0},\vec{r},-t) = v(\overrightarrow{r_0},-t) \otimes v(\vec{r},t) \\ {\varepsilon_z}^{RT}(\overrightarrow{r_0},\vec{r},-t) = \ \varepsilon_z(\overrightarrow{r_0},-t) \otimes \varepsilon_z(\vec{r},t) \end{cases} \tag{4}$$

Under the hypothesis of an ideal isotropic diffuse wave field, the decomposition on plan wave at a given central frequency allows to use approximation of the gradient $\varepsilon_z \approx ik\varphi$ and the particle velocity $v \approx i\omega\varphi$. Then we can write their time reversal fields as in (eq.5).

$$\begin{cases} v^{RT} = \omega^2 \varphi^{RT} \\ {\varepsilon_z}^{RT} = k^2 \varphi^{RT} \end{cases} \tag{5}$$

According to the classical relationship between, the wave vector k and the angular frequency ω we can estimate the local wave speed c_s of the shear waves (eq.6)

$$C_s = \frac{\omega}{k} = \sqrt{\frac{v^{RT}}{{\varepsilon_z}^{RT}}} \tag{6}$$

The displacement at one point is chosen as a virtual source and will be correlated to the other points of the 2D images; this manipulation is the time reversal computation on the computer. Now we only take the measurement at the focus time t = 0s (fig2.a).

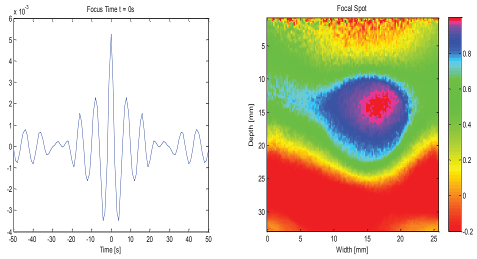

Fig.2. Correlation function of an experimental field. Left hand side: as function of time, we can notice the converging wave at negative times and the diverging wave at the positive time. Right hand side: the focal spot at time t = 0s in a 2D representation.

The locale shear wave velocity at one point will be retrieved by the measurement of the size of the focal spot at time t = 0s (fig2.b).

The tomography is obtained by focusing the particle velocity and the strain field at each point of the 2D field according to the (eq.4). The ratio, according the (eq.5), gives the locale shear wave speed map (fig3.a and b).

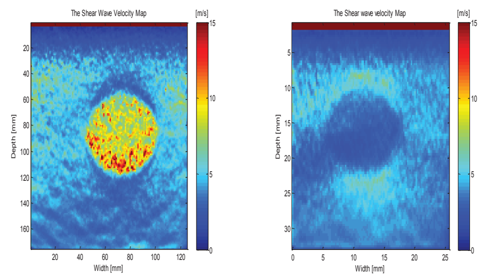

Fig.3. Local shears wave speed maps. retrieved from a diffuse noise-like shear wave field . Left hand side: shear wave speed map of the stiffer inclusion, we measured 7.8 m/s in the inclusion and 4 m/s in the background. Right hand side: the softer inclusion, we measure 3 m/s in the inclusion and 4 m/s in the background.

The two maps in fig.3 show the stiffer inclusion (left hand side) and the softer one (right hand side), this results show clearly the two inclusion with a good contrast of the measured locale shear wave speed. The measured shear wave velocity in the background is 4 m/s, 7.8 m/s for the stiffer inclusion and 3 m/s the softer one. Comparing to the values of the shear wave speed given by the phantom manufacturer (2.88 m/s for the background, 5.16 m/s for the stiffer inclusion and 1.63 for the softer one), we are globally over-estimating the locale shear wave speed. It worth to highlight that, we measure the same shear wave velocity in the background for the both maps, and the ration between the shear wave speed in the inclusion and in the background is in good agreement with the data given by the phantom manufacturer.

We presented in this short study the feasibility of passive elastography approach in CIRS® phantom using an ultrafast ultrasound scanner. The mean objective of the future works, is to resolve the over estimation problem.

References

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