Beamforming Techniques for Motion Estimation in Ultrasound Elastography

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***Abstract*—In this paper, we will discuss about the interest and performance of synthetic aperture with transverse oscillations beamforming technique from the displacement estimation point of view. After the experimental validation of the combination of transmit and receive beamforming for transverse oscillations methods using synthetic aperture imaging, performances in terms of displacement field accuracy are evaluated experimentally. Motion is estimated using a specific motion estimation method based on phase plane fitting. The quality of the estimation is evaluated by block wise correlation between the pre-deformation image and the registered post-deformation image. Results show that transmit and receive beamforming allow to increase by nearly a factor of 2 the transverse oscillations frequency increasing as well the transverse resolution by a factor of $\sqrt{2}$ compared to receive beamforming only. This leads naturally to an increase in estimated displacement field accuracy.**

Keywords: synthetic aperture, lateral oscillations, elastograhy, beamforming, displacement estimation, quantitative experimental validation

I. INTRODUCTION

In the classical beamforming scheme, radio-frequency (RF) images are seen as the convolution between the reflectivity function and a linear kernel, the point spread function (PSF), which features modulation only along the longitudinal axis. This kind of RF images is known to have a bad transverse resolution. Different beamforming techniques have been set up to obtain a PSF that oscillates in both directions to enhance the transverse field accuracy. Images obtained this way are called RF transverse oscillating images. Authors like Jensen *et al.* introduced these techniques in ultrasound blood flow imaging [1, 2]. In the field of elasticity imaging, our team worked on this kind of beamforming techniques to accurately estimate axial and lateral components of the displacement field [3, 4] .

Beamforming techniques for transverse oscillations use the classical delay and sum scheme. Delays are used to dynamically focus the signals all along the RF image. Apodization window are used to create oscillations. These techniques can be divided in two classes depending on how many apodization windows are applied. The first class relies on a unique focalization and apodization window applied on the received signals, so we speak about beamforming in receive (ARX) methods [3]. A second class, based on the processing of a full synthetic aperture (STA) data set to beamform in transmit and in receive, was introduced in [4]. It uses focalization and apodization windows both in transmit and receive. It is shown in [4, 5] that using this kind of techniques leads to faster oscillations and thinner envelope in comparison with the ARX method.

Basarab *et al.* have developed in [6] an analytical displacement estimator that uses the specificity of transverse oscillating images. It is based on phase comparison between two 2D analytical signals of ROIs calculated from the two RF lateral oscillating images. We will illustrate experimentally in this paper that this estimator performs better with faster oscillations and higher resolution transverse oscillations images.

Since we want a quality criterion that can be applied on experimental data, we must build it on the beamformed images and on the estimated displacement field. The displaced image is registered using the opposite displacement field and compared to the initial image using block wise correlation [7].

Studies have been presented in the literature to validate some of those transverse oscillations techniques, but it never relies on the displacement field estimation upgrade. First we validate STA beamforming method itself. Then, we will experimentally compare ARX and STA transverse oscillations beamforming methods, using the displacement field criterion. Standard beamforming method is also computed to fix the origin of the performance scale.

II. USED METHODS

A. *Beamforming techniques*

1) *Beamforming*

Here we use the approximation of a spatially separable PSF $h(x,z)$, which can be written as:

$$h(x,z) = h_e(x)h_r(x)h(z) \tag{1}$$

Where $h(z)$ is the axial profile of the PSF, $h_e(x)$ and $h_r(x)$ are the transmit and receive transverse profiles of the PSF, respectively.

Using delay and sum scheme with a given aperture, if dynamic focusing is used, it is possible to approximate the transverse profile of the PSF in transmit or in receive to the Fourier transform of the aperture function or apodization function in transmit or receive, respectively [8], like shown in (2).

$$F\{w_{e/r}(x_i)\} = h_{e/r}(\frac{x}{\lambda_z}) \quad (2)$$

Where $F\{\bullet\}$ is the Fourier transform operator, $w_{e/r}(x_i)$ is the transmit or receive apodization coefficient of ith element situated at position x_i, $h_{e/r}$ is the transmit or receive transverse profile expressed as a function of λ_z, the wavelength of the transmitted pulse, z the depth of the point of interest, and x its lateral position.

2) STA beamforming

In synthetic aperture imaging, every $r_{ij}(t)$ signals are acquired, where the ith element of the transducer is used to emit the excitation pulse and the jth element is used in reception. From this data set a formed image is calculated by focusing and apodizing signals around the line of interest in emission and in reception [2, 4]. Letting P_k be a point on the line of interest, $O_{i/j}$ be the center of the i/jth crystal and c the speed of sound in the medium, we can express the flight time from the emitting crystal to the receive position as (3). The focus operator is obtained by compensating the flight times (4).

$$t_{tijk} = t_{eik} + t_{rjk} = \frac{\|O_i P_k\| + \|P_k O_j\|}{c} \quad (3)$$

$$foc_{ijk}(t) = \delta(t - t_{tijk}) \quad (4)$$

And the signal beam formed for the kth column of the formed image is calculated using $w_{ek}(j)$ the apodization window in emission and $w_{rk}(i,j)$ the window in reception (5).

$$s_k(t) = \sum_j w_{ek}(j) \sum_i w_{rk}(i,j) \cdot (foc_{ijk} * r_{ij})(t) \quad (5)$$

3) Transverse oscillations

Since we want to obtain transverse oscillations, $h_e(x)$ and $h_r(x)$ are expressed as below (6). It depends on two parameters, the PSF transverse wavelength λ_x and the PSF transverse width at half maximum σ_x.

$$\begin{aligned} h_e(x) &= \sin(2\pi x/\lambda_x)\exp^{-\pi\left(\frac{x}{\sigma_x}\right)^2} \\ h_r(x) &= \cos(2\pi x/\lambda_x)\exp^{-\pi\left(\frac{x}{\sigma_x}\right)^2} \end{aligned} \quad (6)$$

Using (1) and (2), $w_{ek}(j)$ and $w_{rk}(i,j)$ become [4]:

$$\begin{aligned} w_{ek}(x_i) &= \frac{1}{2}(\exp^{(\frac{x_i - x_0 - x_k}{\sigma_0})^2} + \exp^{(\frac{x_i + x_0 - x_k}{\sigma_0})^2}) \\ w_{rk}(x_j) &= \frac{1}{2}(\exp^{(\frac{x_j - x_0 - x_k}{\sigma_0})^2} - \exp^{(\frac{x_j + x_0 - x_k}{\sigma_0})^2}) \end{aligned} \quad (7)$$

With $x_0 = \lambda_z / 2\lambda_x$ $\sigma_0 = \lambda_z / \sigma_x$ and x_k is the position of Q_k along the transducer. For a fixed aperture size (fixed x_0 and σ_0), it is shown in [5] that using STA doubles the transverse frequency and divide width at half maximum by $\sqrt{2}$ with respect of ARX methods. Figure 1 shows the shape of apodization windows.

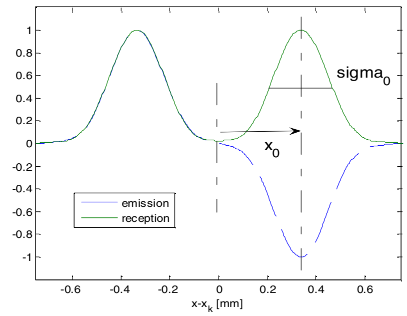


Figure 1 : STA apodization windows

B. Displacement estimators

1) Displacement model

Equation (8) describes the displacement between I_1, the reference image and I_2, the image of the medium under strain.

$$I_2(x,z) = I_1(x + u(x,z), z + w(x,z)) \quad (8)$$

Where u (resp. w) stands for the displacement field along the first direction (resp. second direction).

We estimate the displacement using a bilinear deformable displacement model (BDDM). This model is worth only if the displacement field is small versus the spatial dimension of the images I_1 and I_2. The bilinear model consists on taking the expression (9) for u and v. It lets us describe this displacement field using only 8 parameters $a_u \ldots d_u$ and $a_w \ldots d_w$.

$$\begin{cases} u(x,z) = a_u \cdot x + b_u \cdot z + c_u \cdot x \cdot z + d_u \\ w(x,z) = a_w \cdot x + b_w \cdot z + c_w \cdot x \cdot z + d_w \end{cases} \quad (9)$$

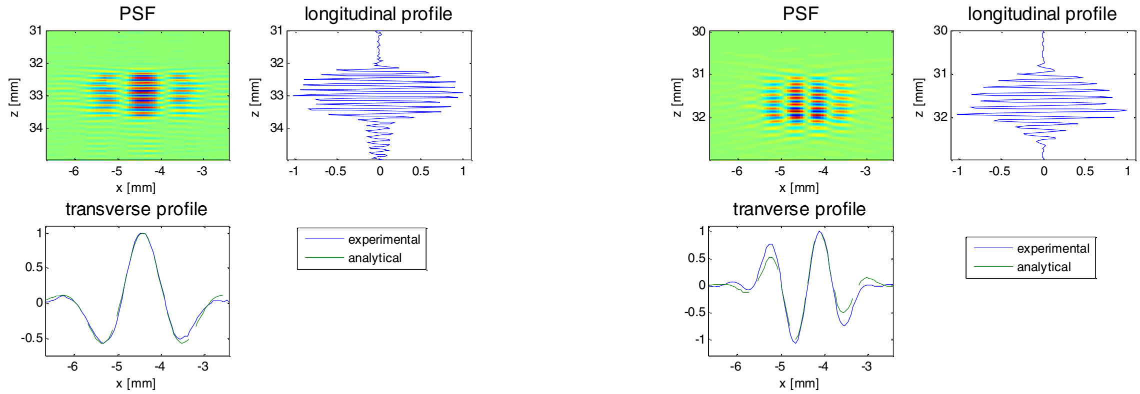
2) Analytical motion estimator

Our team also developed an analytical local motion estimator adapted to transverse oscillating images [6, 7]. Thus, an analytical estimation of sub-sample 2-D local translations based on an *a priori* model of images is obtained. The *a priori* model considered, based on a product of two sinusoids, is issued from the technique of producing transverse oscillating images (6). This local estimator is well adapted to block matching based methods with ultrasound images and is shown to provide better results than classical sum of absolute differences (SAD) or correlation based cost functions [9].

C. Quality criterion

We use the same displacement model as in the motion estimator and we register the deformed image using the opposite estimated displacement field operator $-T_{opt}$ (10). The calculated image $\tilde{I}_1$ must look like the non deformed image I_1 if the field is well estimated.

$$\tilde{I}_1 = -T_{opt} \circ I_2 \quad (10)$$



(a) (b)

Figure 2 : beam formed PSF and profiles using (a) ARX (b) STA

To quantitatively estimate this similarity, a normalized correlation $C_N(\bullet,\bullet)$ is calculated for each corresponding pair of blocks $I_1(i,j)$ and $\tilde{I}_1(i,j)$. The final criterion Q is the average correlation over each block (11). Details can be found in [10].

$$Q = \underset{i,j}{mean}(C_N(I_1(i,j),\tilde{I}_1(i,j))) \qquad (11)$$

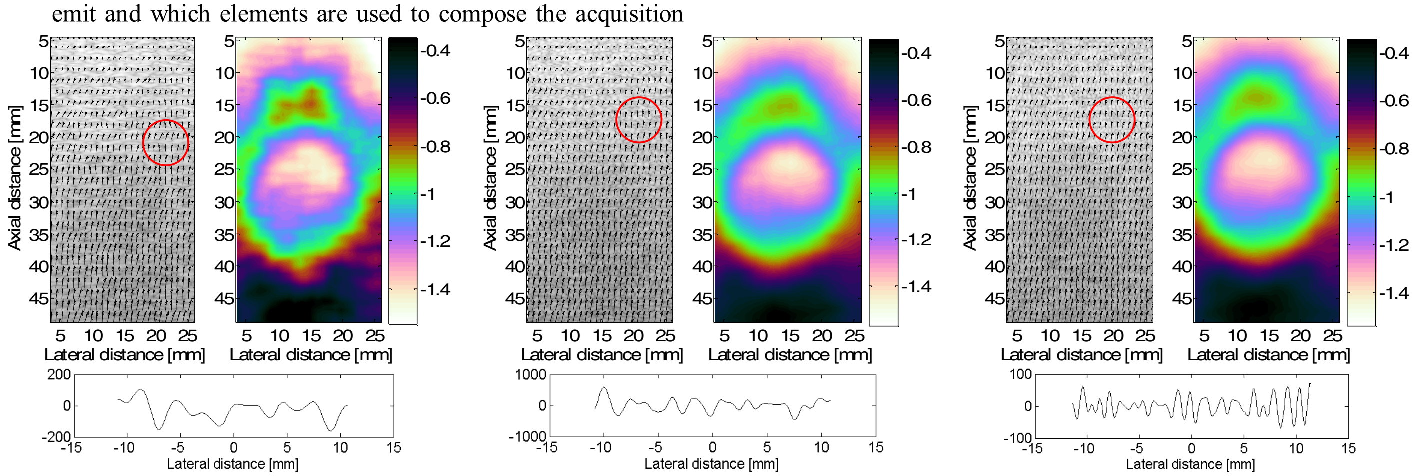
III. Experimental Results

A. Used materials

The RP500 Ultrasonix ultrasound scanner has been used to acquire the data set needed to apply STA with transverse oscillations. Using a SDK provided by the manufacturer, we can build our own imaging sequence, selecting witch elements emit and which elements are used to compose the acquisition line. A 128 elements linear transducer, having its central frequency at 5 MHz. is used together with the 40 MHz ADC embedded in the ultrasound scanner. All the calculation, beam forming and motion estimation, are post treated.

B. Beamforming

First step to experimentally validate STA and ARX beamforming techniques for transverse oscillations imaging. Since we want to compare the performance of those methods, we take the same typical parameters $\lambda_x = 2mm$ and $\sigma_x = 3mm$ for both beam forming method. The images are formed and shown in Figure 2. As predicted in [3-5], the transverse oscillation frequency has doubled while using STA instead of ARX. The transverse profiles fit well the expected profiles, validating the beam forming techniques.



$Q_{\text{standard}} = 93.91\%$ $Q_{ARX+LSP} = 96.75\%$ $Q_{STA+LSP} = 97.25\%$

(a) (b) (c)

Figure 3 : estimated displacement field, axial deformation and transverse profile
(a) RF image + standard block matching with BDDM
(b) ARX with transverse oscillations + LSP (c) STA with transverse oscillations + LSP

C. Motion estimation

The experimental result we present here are calculated using a elasticity phantom “model 049 by CIRS Tissue Simulation & Phantom Technology, USA”. It features a spherical 20mm diameter inclusion of elasticity 17kPa for a surrounding medium of elasticity 29kPa. This inclusion is located at a depth of 30mm. Displacement field is estimated using classical RF images with standard block matching with BDDM, ARX with lateral oscillations images with LSP estimator and STA with transverse oscillations images with LSP. We take the same values as above for the beamforming parameters. Figure 3 shows the estimated displacement field superposed over the initial image on the left. Axial deformation map is shown on the right. A transverse profile is shows on the bottom. Quality criterions are given for each method

IV. Discussion

Transverse profiles displayed in figure 3 qualitatively show the increase of the transverse modulation frequency. Central wavelength of transverse profiles is $2mm$ for ARX and $1.1mm$ for STA. Typically reached transverse frequency is 10% of longitudinal modulation frequency. Performance upgrade of STA versus ARX for transverse oscillations, highlighted in [5] using simulations is experimentally validated.

Circles highlights region of interest where the increasing regularity of the estimated field from figure 3(a) to 3(c) can be seen. The smoothness of axial deformation map is a good hint of the upgrade brought by STA images.

Quality criteria are quantitatively validating the interest of STA for transverse oscillations for displacement estimation since the highest value is reached for this method.

$$Q_{\text{standard}} < Q_{ARX+LSP} < Q_{STA+LSP} \qquad (12)$$

V. Conclusion

In this paper we have compared two innovative ways of forming ultrasonic images ARX and STA beamforming coupled with transverse oscillations and a specific displacement field estimator. Using a quantitative criterion, we showed that for the same number of physical element used, STA with transverse oscillations was the best choice. We have shown the increasing performance of the method developed by our team, validating experimentally the simulation results already published in [4].

The next step is to use this approach on a clinic data, like for example on thyroid data. This project should be carried out with a cooperation work with the partner hospital team.

VI. Acknowledgment

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VII. References

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