MULTI RESOLUTION TRANSVERSE OSCILLATIONS FOR MOTION ESTIMATION IN ULTRASOUND IMAGES

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ABSTRACT

In recent work, motion estimation in ultrasound (US) image sequences has been conducted thanks to a phase based motion estimator working with the so-called transverse oscillations (TO) images obtained using specific beamforming in reception. In this paper, the nonlinear behavior of the medium is considered and the TO images are created at the fundamental but also at the second-harmonic frequency. With such images, a multi resolution transverse oscillations (MRTO) approach has been designed in order to measure the motion in US images sequences. A first estimation is conducted on the TO fundamental image, which is then improved by the TO second-harmonic one. The resulting motion estimation, quantitatively assessed both in simulations and experimentally, is strongly improved, in terms of mean motion value and standard deviation, compared to the motion estimated only using the fundamental TO image. The resulting error is reduced from 35% to 7% for high displacement values.

Index Terms— Ultrasound, motion estimation, nonlinear propagation, transverse oscillations, phase, multi resolution

1. INTRODUCTION

Motion estimation in ultrasound (US) imaging has become a classical way to obtain additional information to improve diagnosis as, for example, in elastography [1], blood flow [2] or strain imaging of the heart [3]. Previous studies have shown the interest of using the specific, so called, transverse oscillations (TO) images along with a phased-based motion estimator to evaluate the displacement in case of blood flow [4, 5], elastography [6-8] and more recently echocardiography [9]. An overview of different beamforming strategies, estimation techniques and applications of transverse oscillations can be found in [10].

The TO are created in the radio frequency (RF) US images using specific beamforming strategies. They are based on a dynamic quadratic focusing and a specific apodization function to create axial and lateral oscillations. The resulting point spread function (PSF) shows oscillations in both spatial directions. The maximum lateral motion is limited by the half wavelength of the oscillations in the lateral direction. On the other hand higher frequency (lower wavelength) TO would lead to more precise estimates in case of small displacements. Both statements are contradictory. As a result it would be interesting to benefit of a multi-resolution approach of TO. Images with a long lateral wavelength could be used to estimate the largest displacements and the solution could be refined using images with shorter TO.

Here we propose such a multi resolution transverse oscillations (MRTO) scheme. We exploit the nonlinear propagation of the US in biological media in order to compute the second-harmonic TO image. This image has the nice property to have an oscillation wavelength twice shorter than in the fundamental image. The two resolution levels in the motion estimator are used to increase the accuracy of the phase-based method.

The paper is organized as follow: in section 2, the mathematical background of TO and MRTO is developed. Then, section 3 presents the obtained results in simulation and experimental cases. Then, discussions and conclusions are conducted.

2. MULTI RESOLUTION TO METHODOLOGY

2.1. Description of transverse oscillations

Initially developed for blood flow estimation [4], TO have been used for other applications and several descriptions can be found in the literature as summarized in [10]. In this study, a received only approach is used, which means that the TO are created by using a specific beamforming strategy only during the receive process. An illustration of the receive scheme is proposed in Fig. 1. A plane wave is transmitted in order to affect as less as possible the shape of the final PSF. The receive beamformer is designed according to Fraunhofer approximation (FA) [11]. The pre-beamformed RF signals, received on the active elements of the probe, need first to be dynamically focused in order to respect the FA. The apodization function is chosen as the inverse Fourier Transform of the expected profile. As the transverse profile is expected to exhibit an oscillatory pattern limited by a Gaussian window [6], the following apodization function in reception, w_r, is used:

$$w_r(x) = \frac{1}{2}\left(e^{-\pi\left(\frac{x_r - x_0}{\sigma_0}\right)^2} + e^{-\pi\left(\frac{x_r + x_0}{\sigma_0}\right)^2}\right) \quad (1)$$

where $2x_0$ is the distance between the two Gaussian peaks and σ_0 is their width at half maximum. In order to access to

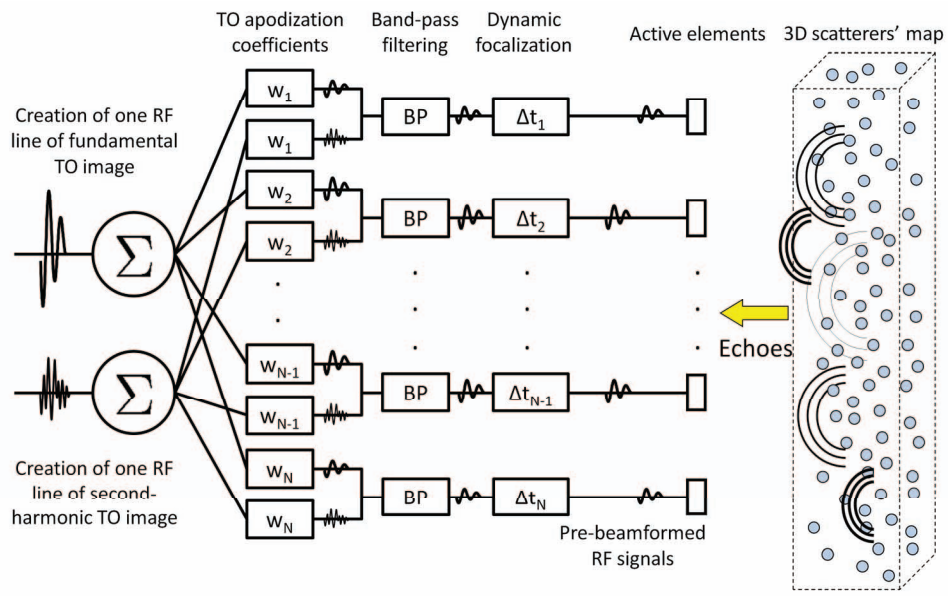


Fig. 1. Illustration of the reception scheme for fundamental and second-harmonic TO beamforming. From the echoes of the scatterers of the medium, the elementary RF echoes are received, focalized before to be filtered in order to create the two different TO images.

a constant PSF as a function of the propagation distance, these two values are defined as:

$$\begin{cases} x_0 = \lambda z/\lambda_x \\ \sigma_0 = \sqrt{2}\lambda z/\sigma_x \end{cases} \quad (2)$$

where λ is the signal wavelength, λ_x and σ_x are the wavelength and the width at half maximum of the lateral profile of the PSF, respectively. It can be observed from equation (2) that to maintain a constant PSF in the lateral dimension, the values of x_0 and σ_0 have to be adapted as a function of the depth. The two dimensional representation of the receive apodization function is given in Fig. 2 and the used parameters in Table I.

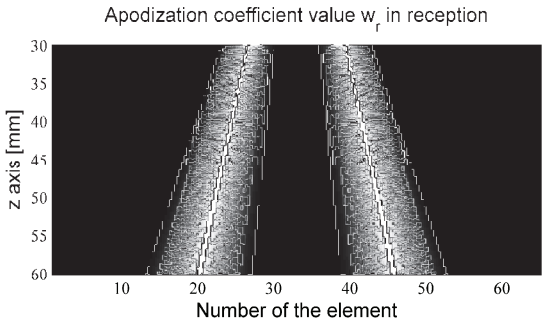


Fig. 2. Apodization function in reception with adapted value of x_0 and σ_0 to keep the PSF with constant dimensions.

2.2. Multi resolution TO

The linear description of the US wave propagation in tissues or biological media is an approximation of the reality. Indeed, during the propagation, the nonlinear behavior of the media distorts the pressure pulse and harmonics appear. Tissue harmonic imaging (THI) provides a higher resolution and is currently used in clinical exams [12]. During the TO beamforming, it is possible to filter the pre-beamformed data in order to access to the second-harmonic pre-beamformed signals. Then, the same TO beamforming scheme is used. Practically, the same apodization function $w_r(x,z)$ is used on the pre-beamformed data. While the axial oscillations frequency is increased by a factor of two, the lateral oscillations frequency is also increased by a factor of two, according to equation (2). The resulting obtained PSF, for the fundamental and second-harmonic images, are presented in Fig. 3. The parameters used for the probe and the transmitted plane wave are given in Table I.

TABLE I. PROBE AND SIGNAL PARAMETERS

Parameter	Value
Height	12.5 mm
Pitch	245 µm
Kerf	30 µm
Number of active elements	64
Transmit focus	∞
Elevation Focus	22 mm
Transmit frequency	5 MHz
Number of cycles	7
Window	Hanning

2.3. Motion estimation using MRTO

The previous section has shown that the lateral and the axial wavelengths are twice smaller in the second-harmonic TO image compared to the fundamental one. To measure the motion between two images, a phase-based method, previously described in [13], is used. To increase the accuracy of the motion estimation compared to the conventional single frequency TO approach, the following

three steps scheme is used: i) a first estimation is conducted using the fundamental TO images, ii) then, the motion obtained from the low resolution images is compensated for in the second harmonic images, iii) a second estimation is performed using the second harmonic compensated images in order to refine the first estimate.

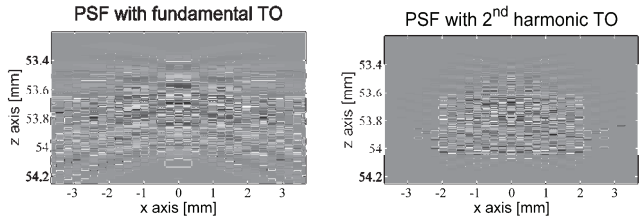


Fig. 3. Simulated TO PSF using the fundamental (left) and the second-harmonic (right) RF data.

3. RESULTS

The MRTO has been evaluated on simulated and experimental data. In all experiments, the λ_x and σ_x values have been set to 2.45 mm and 7.35 mm, respectively. These values have been chose to obtain the fewer PSF on the second harmonic data.

3.1. Simulation settings

To simulate the US data, the CREANUIS software has been used [14] and several images have been generated with moving scatterers. This software simulates the pre-beamforming fundamental and second-harmonic RF data with the desired probe geometry and beamforming strategies in transmission.

In CREANUIS simulations, a random reflectors map has been used and eight images have been generated with a pure lateral displacement of the scatterers in the range [0; 0.7mm], by step of 0.1 mm. The geometric properties of the LA523 probe, described in Table I, have been used. Only a lateral displacement has been set in these cases. To ensure a sufficient speckle in the US image, 20 scatterers per mm^3 have been used. The same signal has been transmitted in the different media. It consists in a plane wave of 7-cycle sine at 5 MHz with a Hanning window. This high number of cycles has been transmitted in order to introduce energy and then emphasize nonlinearity during the propagation.

The beamforming in reception has been conducted off-line using Matlab (The Mathworks Inc., Natick, MA, USA). It consists in, first, doing the dynamic focusing, second, generating the pre-beamformed fundamental and second-harmonic images, and finally, creating the two corresponding TO images. These operations are repeated for each data-set with moving scatterers position.

3.2. Experimental settings

In experimental measurements, the open platform ULA-OP has been used [15]. This research scanner allows to save the pre-beamformed data for the different acquisitions. The LA523 probe is used and a commercial homogeneous phantom (CIRS elastography phantom, model 049) has been used. As in simulation, the same plane wave has been transmitted in the medium. Using the same beamforming scheme in Matlab, the corresponding TO images have been generated.

To impose and quantify the motion between two experimental images, a micrometric table has been used to impose the same displacement as in simulation. In this case, a particular attention is required in order to impose a translation only in the lateral direction. These displacements can now be estimated with the MRTO technique described in the previous section. As in simulation, only a lateral displacement has been imposed in these experiments.

3.3. Motion estimation results

The motion estimation is conducted in different regions of the images. On each part, the classical evaluation of the motion is conducted using the fundamental TO image and then the MRTO method. The resulting estimations of the displacement are presented in Fig. 4.a in simulation and in Fig. 4.b for the experimental case. For each case, the mean value of the displacements has been estimated as well as the standard deviations. For the two studied cases, the resulting estimation of the displacement with the MRTO is more accurate than the estimation realized only on the fundamental image. The motion is correctly measured for higher displacement value and the standard deviation is strongly reduced around the mean value. With a 0.7 mm displacement, the error is reduced from 43% to 4% in simulation and from 34% to 7% in experiments.

4. DISCUSSION AND CONCLUSION

Using the two resolutions of TO images, the MRTO is able to improve the estimation quality compared to the previous TO methods. To summarize, the motion with high displacement value is first estimated on the fundamental image, with the TO image at frequency f, and then refined with the second-harmonic image, with the TO image at frequency $2f$. In simulations or in experimental case, the MRTO allows to measure accurate displacement in US images. The resulting estimations are better compared to the estimation only based on fundamental images. Indeed, the motion estimation on the second-harmonic TO image presents a higher resolution which allows to improve the initial estimation and to reduce the standard deviation. The evaluation of the method needs to be tested in more realistic cases as for example with compression in elastography applications which would lead to more sophisticated motion patterns (deformation, rotation etc…).

The MRTO method is not limited to the second-harmonic TO image. Theoretically, the pre-beamformed data not only contains the two first harmonics but also the third, fourth… As a result, the beamforming could be conducted on each filtered image and then, the motion

estimation could be improved using the higher resolution TO images. However, in experimental images, the band-pass of the probe is limited in transmission and reception, and receive the third-harmonic is very difficult. New capacitive micro-machined ultrasound transducer (cMUT),

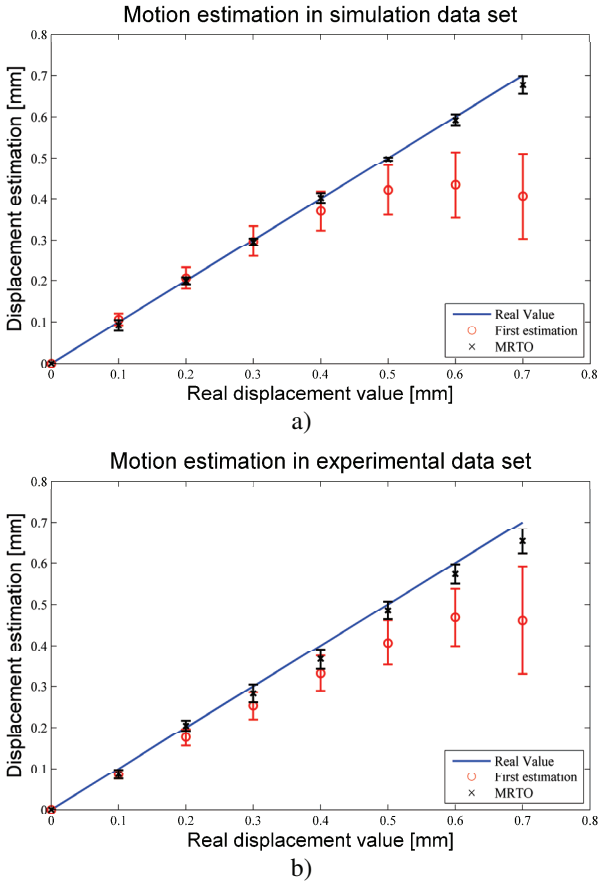


Fig. 4. Motion estimation results in simulation (a) or in experimental (b) data set. The MRTO provides the more accurate results.

having a theoretical infinite band-pass in reception, are particularly suitable for MRTO with higher frequencies. The second limitation of MRTO with higher frequencies comes from the lateral sampling required. Indeed, the lateral wavelength of the oscillation must at least be exploitable in the TO image in order to estimate the motion displacement with the phase-based estimator.

5. ACKNOWLEDGMENTS

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