SIMULATION OF AUTOMATIC SELECTION IN MULTI-TARGET MEDIUM USING TIME REVERSAL MIRROR

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In high intensity focused ultrasound (HIFU) therapy, the focusing of acoustic waves in inhomogeneous media is a common and difficult problem to solve. The focusing can be strongly degraded by sound speed variation and density variation from geometrical distortion. The time reverse mirror is a solution to this problem when the target is a reflective one, even when the location of the target is unknown. The iterative time reversal mirror is also used to automatically select the strongest target in a multi-target medium. To simulate the acoustic fields of iterative time reversal mirror and evaluate its convergence, the FEM time-dependent model is used. Three cases of time reversal process in multi-target medium are presented. It is shown that in these three cases, the iterative time reversal process has the ability to focus on the strongest target. And the effectiveness of convergence is discussed in these three cases.

Keywords: HIFU; Time reversal mirror; Automatic selection

1. INTRODUCTION

High intensity focused ultrasound (HIFU) is a fast evolving medical technology for noninvasive surgery[1]. When ultrasound is strongly focused on the target issue, the local temperature can increase to 60℃ or higher within a few seconds of exposure. This leads to thermal coagulation necrosis at target tissue, while surrounding healthy tissue is minimally affected. Therefore HIFU has an advantage as a noninvasive therapy. HIFU has been successfully applied for treatment of tumors in the pancreas, kidney, prostate, and other tissues of human body in clinical trials or clinically[2].

The focusing of an ultrasonic wave on a fixed or moving target is often degraded in inhomogeneous medium. Such problem occurs in different medical applications such as hyperthermia or lithotripsy[3]. The focal point is not accurate when sound waves propagate in inhomogeneous media. Conventional means for acoustic focusing such as concave transducers, mirrors, phased arrays work very well in homogeneous medium, but it is hard to apply them in inhomogeneous medium[4].

The acoustic time reversal mirror (TRM) is a good solution to this problem when the required focal point is a reflective target The concept of TRM is proposed by Fink in 1989[3], which has the ability to transmit or receive a wave. The reflective signal can be separated from the received one, then reversed and re-emitted. Meanwhile, TRM process can be iterated: the backscattered waves are recorded, time reversed, and transmitted again at each iteration. This iterative mode allows the ultrasound to automatically focus selectively on the brightest reflective target when several targets are in the medium [5, 6].

In the cases of more complicated media which contain numbers of dense targets, the outcome of iterative process is not well studied. In this paper, the simulation of time reversal acoustic field is implemented. Several targets are embedded in homogeneous or inhomogeneous medium to demonstrate the efficiency of the iteration in focusing on the strongest target. The accuracy of convergence are also discussed.

2. TIME REVERSAL MIRROR THEORY

An acoustical wave propagation in an inhomogeneous and lossless medium can be described by the pressure field $p(r,t)$, where r and t are the space and time coordinates. $c(\mathrm{r})$ is acoustic velocity. And $p(r,t)$ satisfies the wave equation:

$$\Delta p - \frac{1}{c(\mathrm{r})}\frac{\partial^2}{\partial t^2}p = 0 \, . \qquad (1)$$

Because the time derivative is second order, given $p(r,t)$ the solution of this equation, $p(r,-t)$ is also a solution. In other words, the equation is time invariant after time reversal process. In fact, the time reversal can be done on a period, and $p(r,\mathrm{T}-t)$ becomes a solution of the equation as well.

The TRM process is performed in three steps.

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(1) The mirror transmits a broadband signal through the medium which contains the reflective target.

(2) The mirror acts as a receiver, the pressure wave that is reflected by the targets is received by the mirror. N signals are received by the N transducers.

(3) The mirror acts as an emitter, where the received signals are time reversed and reemitted by the mirror.

The steps of how TRM works are shown in Fig. 1 (a)-(c), corresponding to steps (1) to (3). These steps can be iterated to select the brightest target in a multi-target medium

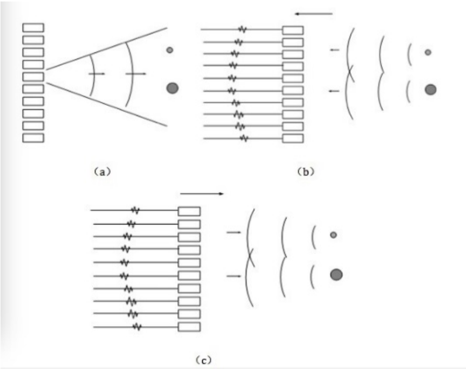

Figure 1. Steps of time reversal mirror in multi-target medium

3. MODELS AND NUMERICAL SIMULATIONS

3.1 models

To simulate the acoustic fields of TRM and evaluate its convergence, the FEM time-dependent model is used. An ultrasonic transducer array of 32 elements is placed at the top of the computational region as a time reversal mirror. The inter-element spacing of the transducer is 2.5mm.

Three cases of time reversal process are simulated and the material models are shown in Fig. 2-4. In the first case, the medium is homogeneous except for two reflective targets. In the second case, two targets are embedded in a tissue-like layered inhomogeneous medium. In the third case, the tissue-like layered inhomogeneous medium contains three targets which are close to each other with inter-targets spacing of 5mm, which is only 1.6 times larger than wave length. The parameter used in the models are listed in Table.1.

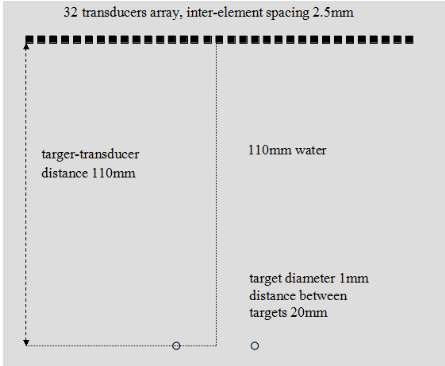

Figure 2.Model 1. Two targets in homogenous medium

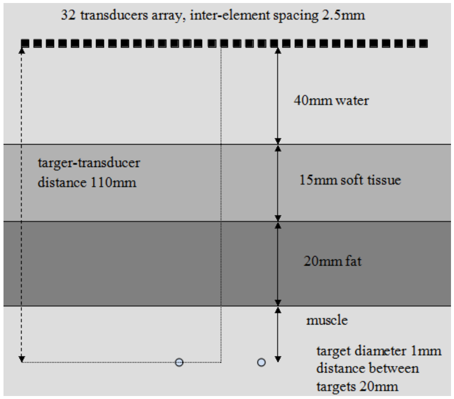

Figure 3.Model 2. Two targets in inhomogeneous medium

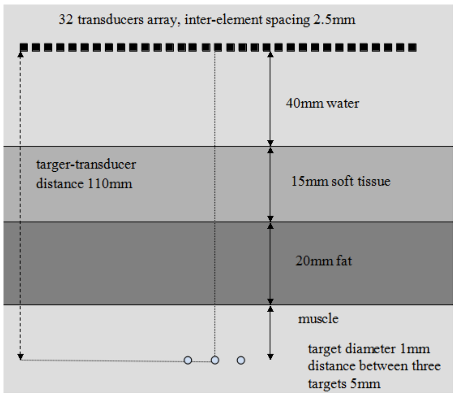

Figure 4. Model 3. Three targets which are close to each other in inhomogeneous medium

3.2 Source condition

Before starting iteration process, a time reversal signal should be created. As shown in Fig.1(a), a transient sound wave is emitted by transducer No.17 of 32 transducers in Fig2-4 at the very first time. Then iterative process starts. The signal used for the first emission appear to be

$$S(\mathrm{t}) = \exp(-(2\pi f_0)^2 (\frac{t-1.5/f_0}{1.5})^2)\cos(2\pi f_0(\mathrm{t}-\frac{1.5}{f_0})) \,. \quad (1)$$

Where f_0 is the center frequency. In subsequent iterations, the reflected time reversed signal will be used as transmit signal.

Table 1. Properties of materials

Material	*Density* (10^3 kg/m^3)	*Velocity* (m/s)
Water	1000	1500
Soft tissue	1016	1500
Fat	955	1476
Muscle	1074	1568
Weak Target(left in case I II, left and right in case III)	1500	1500
Strong Target(right in case I II, middle in case III)	2000	1500

3.3 Results

In this section, we present the resulted sound field of numerical simulation of time reversal mirror generated by a 32-element transducer array. The center frequency of emitted sound wave for the first step of TRM process is 500kHz. Three cases described in the previous paragraphs are simulated and the sound pressures on the focal plane at each iteration step are compared. Then the accuracy of focal spot is discussed.

In the first simulated model where the medium is homogeneous and two targets are implanted, we use a simple model to verify the validity of iterative time reversal process. The comparison of normalized pressure at each iteration step is shown in Fig.5. The distribution of sound pressure field near the reflective targets is shown in Fig.6. The pressure on the weaker target is only ten percent of that on the stronger target. The peak position of the focal spot shifts by 0.5mm along y axe direction compared to the center of the target.

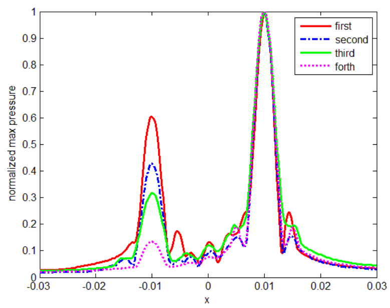

Figure 5. Comparison of normalized pressure of each iteration in case I.

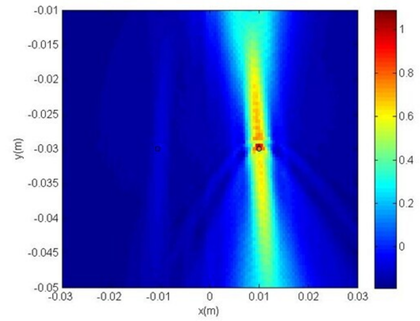

Figure 6. Distribution of sound pressure field near focal point in case I.

In the case II and case III, the medium condition and targets condition are more complex, as shown in Fig. 3-4. From the simulation results of case II (see Fig.7-8), the sound pressure on the weaker target is less than one tenth comparing to the pressure on the stronger target after four iterations, and the peak position of focal spot shifts by 0.5mm along y axe direction comparing to the center of the stronger target.

In case III, the simulation results are shown in Fig.9-10. It seems that the third and the forth iterations of TRM make little difference comparing to the first two iterations. Sound pressure ratio of the weaker targets to the strongest target is approximately 1/5,

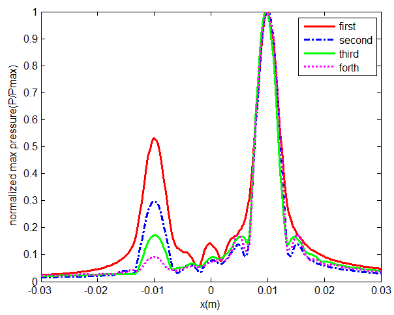

Figure 7. Comparison of normalized pressure of each iteration in case II.

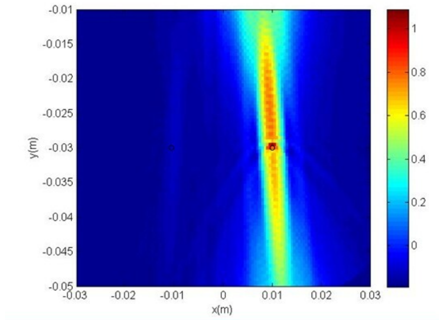

Figure 8. Distribution of sound pressure field near focal point in case II.

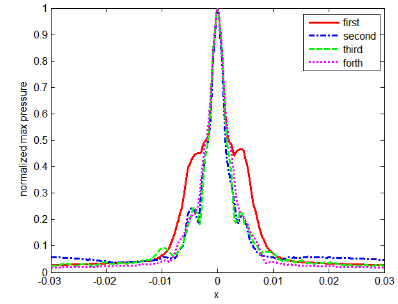

Figure 9. Comparison of normalized pressure of each iteration in case III.

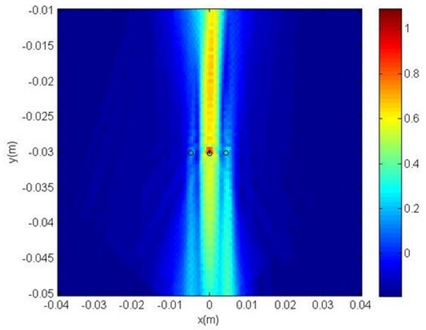

Figure 10. Distribution of sound pressure field near focal point in case III.

which is acceptable. The position of the focal spot is right at the center of the strongest target, which shows the focusing accuracy.

Iterative time reversal process works fine in all the three cases above. In the first iteration of the first case, two lobes are observed in the plane of targets. With the number of iteration increasing, the weak lobe gradually disappears and the strong lobe remains. In the second case, the results of TRM process is similar in the tissue-like inhomogeneous medium as those in the homogeneous medium. In the third case when three targets are very close to each other, the acoustic waves focus on the strongest target as well. Although after four iterations, the effect of iteration becomes less obvious than that in the cases of two targets, the main lobe is still much larger than the side lobes after several iterations. The iterative time reversal process still works, but the selective efficiency decreases after four iterations.

4. CONCLUSION

The iterative time reversal process is conducted by numerical simulation. The efficiency of the method to selectively focus on the strongest target is shown when several targets exist in the media. Three cases of material models are presented and iterative time reversal process are applied by numerical simulation. From the simulation, we can obtain the position of focal spot and the sound pressure distribution, thus evaluate the effectiveness and efficiency of iterative time reversal process. In all three cases, it is shown that the iterative time reversal process has the ability to focus on the strongest target. The sound pressure on the weaker targets can be reduced to approximately 10%~20% of that on the stronger targets after four iterations. The shape of acoustical focal region is a long ellipse. The performance of time reversal mirror is excellent in case I and II in which the targets are well resolved, and acceptable in case III in which the targets are not well resolved. However the focusing accuracy performs quite well in all cases. The shift of focal point is less than 1/2 wavelength. No large shifts are observed.

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