SELECTIVE SOURCE REDUCTION TO IDENTIFY MASKED SMALLER SOURCES USING TIME REVERSED ACOUSTICS (TRA)

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ABSTRACT. This paper introduces a method to selectively reduce large time-reversed focal events to provide the potential to illuminate smaller events which have been masked by the larger one. The method is demonstrated for two elastic wave pulses emitted simultaneously from two spatially separated sources. The method improves upon the spatial resolution abilities of time reversed acoustics in nondestructive evaluation applications to identify characteristics of a sample such as cracks (nonlinear elastic wave scattering sources).

Keywords: Time Reversal, Time Reversed Acoustics, Crack Detection, Source Characterization
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INTRODUCTION

Time Reversed Acoustics (TRA) is a method to focus wave energy onto a specific location in space and time [1]. The common application of TRA consists of a forward propagation step and a backward propagation step. In the forward propagation step, a source emits wave energy which travels through a medium and is detected by one or more receivers. The signals detected at each receiver are reversed in time and rebroadcast from their respective receiver positions. The set of receivers is usually referred to as the Time Reversal Mirror (TRM). The paths traversed in the forward propagation are also traversed in the backward propagation. The wave energy, which retraces these paths, simultaneously arrives at the original source location in phase to produce a time reversed focus.

Bou Matar *et al*, Gliozzi *et al*, and Ulrich *et al* have shown that one may use Time Reversal (TR) and Nonlinear Elastic Wave Spectroscopy (NEWS) to find cracks, which behave as nonlinear scatterers [2-4]. This method is called TR-NEWS. The method consists of sending in a Continuous Wave (CW) signal and introducing a broadband impulse into the sample. The sample filters the broadband impulse according to its modal response. At the crack, the modal frequencies nonlinearly mix with the CW signal to produce harmonics and sum and difference frequencies. It is assumed that the rest of the sample behaves linearly (assuming small wave displacements) and therefore the only nonlinear signals generated emanate from the crack. A set of receiver transducers then records the wave field at each of their respective positions. In order to enhance detection, a narrow band pass filter is applied to the received signals to keep only wave energy from a selected nonlinear mixing frequency. These filtered signals are then time reversed and

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rebroadcast into the sample. Since the energy which is rebroadcast originally emanated from the crack, the time reversed signals will focus this energy back onto the crack and therefore illuminate the crack region. Experimentally, one can scan the surface of the sample with a laser vibrometer to identify surface cracks which have been illuminated as Ulrich *et al* have shown. For buried cracks, the rebroadcast step must be conducted numerically in an accurate model of the sample. Gliozzi *et al* have shown that a numerical model can be used to identify buried cracks using TR-NEWS, though their results are entirely from numerical modeling (including the forward propagation) [3]. To date, it has not been shown that one can do the forward propagation experimentally to excite a crack and then use a numerical model to back propagate the nonlinear component to the crack.

In blind, multiple or complex source problems such as in crack detection for Nondestructive Evaluation (NDE), TRA may be used to reconstruct the complex source [2]. A limitation in TRA is the limit in spatial focusing due to diffraction processes which greatly affects TRA in reconstruction of complex sources whose individual components are in close proximity in space and time. We are unaware of any available method which allows one to improve upon the limitations inherent in complex source reconstruction using TRA, without modification of the source or medium (e.g., addition of nearfield scatterers [5]), without *a priori* knowledge of the source signal(s) (e.g., using an acoustic sink [6-7]), and/or introducing an amplification of the nearfield using nearfield detectors [8].

SELECTIVE SOURCE REDUCTION

The Selective Source Reduction (SSR-TRA) method selectively eliminates or reduces in amplitude a time reversed focal signal that is masking another time reversed focal signal. This method can be successfully accomplished with a single receiving transducer, although additional receivers improve the results. The forward signals are detected, time reversed and sent back to the source(s). For a complex source, it is conceivable that a reconstructed strong source may mask a nearby weak source (or two close-proximity, equal amplitude sources may mask each other by merging into a single focus).

The procedure proposed here consists of the following protocol, schematically reported in Figure 1. Step 1: Let us assume we start with a system in which some signals are recorded at the receivers (Figure 1a). Number of sources, locations and shape of the injected signals are the unknowns. Step 2: Apply the TRA procedure, i.e. signals are time reversed and rebroadcast back from the receivers (Figure 1b). It is expected that the location of a dominant source (let us call it S_1) can be easily identified, corresponding to the position where the displacement is maximum. It is therefore possible to locate an additional receiver (such as a laser vibrometer in the experimental application) in the position of S_1 and repeat the backpropagation experiment now recording the focal signal. Step 3: Rebroadcasting of the time reversal of this dominant focus should then correspond approximately to the solution expected when only the masking source is active, hence providing signals at the receivers which can be considered as approximate reference signals (Figure 1c). Step 4: Considering the original signals as the approximate sum (exact, except for noise contribution, if the material is perfectly linear) of the independent contributions from the sources, we can build a set of signals by subtracting the reference signals (obtained from Step 3) from the original signals (obtained from Step 1). This ideally results in information pertaining only to the masked source, S_2. Subtraction of the signals can be performed only after introducing a proper normalization of the sets of received signals. Finally, the subtraction result is time reversed and rebroadcast. Focusing is expected on the source which was masked (Figure 1d).

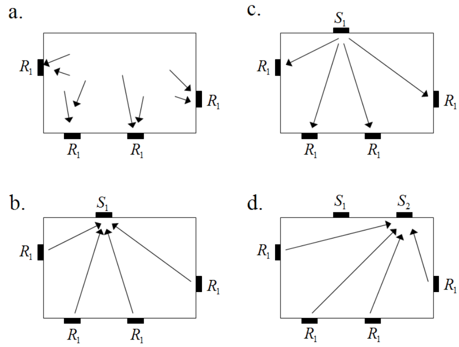

FIGURE 1. Schematic representation of the steps utilized in the selective source reduction method. a. A set of receivers detects original signals from two unknown sources. b. The standard time reversal process is used and only the dominant focus at S_1 is apparent (smaller focus at S_2 has been masked). c. The focus detected at S_1 is time reversed, sent into the sample and detected at the receivers. d. The two sets of received signals at R_{1-4} are subtracted, time reversed, and rebroadcast, and a focus is revealed at S_2.

In each simulation and experimental demonstration of the SSR-TRA method, sine wave signals, modulated by a sine squared envelope, were sent from S_1 and S_2 of the form

$$u(t) = A\sin^2\left(\frac{\pi}{\Delta\tau}t\right)\sin(2\pi ft), \qquad (1)$$

where A is the amplitude, $\Delta\tau$ is the pulse width, t is time, and f is the sine wave frequency. The sine squared term applies an envelope to the signal.

NUMERICAL STUDIES

To perform the numerical analysis, we consider a specimen with physical characteristics corresponding to a metal block of dimensions 8x6x5 cm. The volumetric mass density is 2770 kg/m³ and the longitudinal and shear wave velocities are 5098 m/s and 3064 m/s, respectively. Attenuation is neglected in the simulations. The specimen has two point like sources, S_1 and S_2, located on one surface. Also, an array of five equally spaced receivers is arranged on the opposing surface. The receivers/sources act as sources/receivers when the rebroadcast step is considered. Their arrangement has been chosen to avoid any possible symmetry in the configuration used. The sources simultaneously inject pulse signals (amplitudes vary) with angular frequency 1.26 MHz. Simulations were performed using the Local Interaction Simulation Approach (LISA) [9-12] for a full 3-D elastic description of the wave propagation. A discretization of the specimen with space and time steps of 0.1 mm and 10^{-8} s, respectively, has proven to guarantee stability and convergence.

We have conducted a simple SSR-TRA modeling experiment with two sources of different amplitudes. Numerical results of the propagation of the time reversed signal are reported to show the resulting focusing. A large time-window (1.1 ms) of the detected signals is used for the time reversal, to compensate for the small number of receivers by exploiting the information contained in the coda (coda includes detection of direct arrival and multiple reflections).

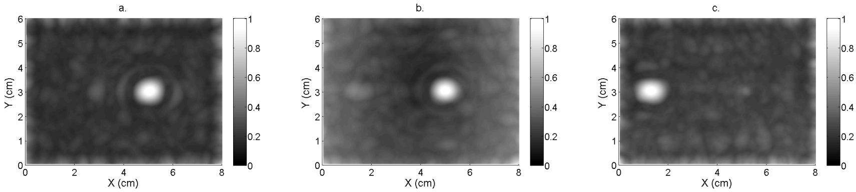

FIGURE 2. Spatial maps of the maximum displacements, demonstrating the selective source reduction in numerical simulations. Initially S_1 (x=5, y=3) is 10 times greater than S_2 (x=1, y=3). a. Result after employing standard time reversal. b. Result after applying the proposed method. c. Result after iteratively applying the proposed method. S_2 is progressively more illuminated from a. to c.

Iteration of the procedure can be applied to obtain progressive cancellation of the dominant source and/or illumination of other minor sources. At step 4 we record the signal in the position of the dominant source, time reverse it (windowing it to zero out everything but the focus), and rebroadcast it. Then, we record the signals at the receivers positions and build a new subtracted signal. Finally, we time reverse and rebroadcast it.

To explore the feasibility of the iteration we have considered a ratio of the original input amplitudes of $A_1 = 10A_2$. In Figure 2a we report a plot of the maximum displacement on the surface of the specimen containing the sources as results from the usual TRA procedure. As expected, the weak source is not illuminated. The first iteration of the selection procedure (Figure 2b) indicates partial illumination of the lower amplitude source, but still S_1 is by far the dominant one. Finally, after iteration of the procedure we observe that only the weaker source is illuminated and S_1 has been reduced (Figure 2c).

EXPERIMENTAL STUDIES

An aluminum slab measuring 80cm in length by 33 cm in width with a thickness of 5.08 cm was used in this study. The sample had piezoelectric ceramic transducers bonded to it with 5 Minute® epoxy. A diagram of this sample may be found in Figure 3. Two sources, S_1, and S_2 were positioned 10.16 cm apart, on one side of the slab and four receivers, R_1, R_2, R_3, and R_4 were positioned 5.08 cm apart, on the other side of the slab as shown in Figure 3. All sources and receivers used on this sample were 1 MHz resonance PZT-5H ceramic transducers disks measuring 2 mm in thickness and a diameter of 12.7 mm. All transducers were bonded to the sample in the same vertical plane but shifted relative to each other such that no transducer was directly across from another (see Figure 3).

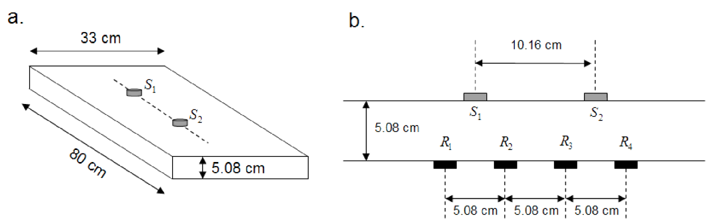

FIGURE 3. Schematic drawings of the aluminum slab sample. Drawings in subplots a. and b. correspond to three-dimensional and cross-sectional drawings of the aluminum slab sample respectively. S and R represent sources and receivers, respectively.

The limits in the performance of the SSR-TRA method were investigated by injecting the same waveforms, in terms of frequency content, to each transducer with different amplitudes ($A_1 \geq A_2$). A signal to noise metric was developed to monitor the quality of the time reversed focal signal. This metric, ψ, is defined as the ratio of the peak of the time reversed focal envelope amplitude (peak near the focal time) to the peak amplitude of the highest side lobe. For example a ratio of 1.0 corresponds to essentially no focal signal whereas a ratio of 5.0 means that the focal signal is five times higher than the highest side lobe.

Figure 4 displays time reversed focal signals at S_1 (subplot a.) and S_2 (subplot b.) before and after performing the SSR-TRA method on S_1 (the dominant source) for an A_1 over A_2 input ratio of 2.63. The plots in Figure 4 show that the focal amplitude at S_1 decreases while the focal amplitude at S_2 increases after performing the SSR-TRA method on S_1, as desired. The reason for the increase in focal amplitude at S_2, instead of the expected reduction in side lobe energy in the focal signal, is due to the fact that the forward detected received signals were always amplified before rebroadcasting the time reversed signals.

We note that the time reversed focus at S_1 is not entirely removed, instead a significant remnant of the focus remains in terms of amplitude, but the temporal distribution is greatly modified. The reason for the amplitude remnant of the focus and the change in the temporal distribution will be addressed in the discussion portion of this paper. Despite the presence of the focal remnant at S_1, the focus at S_2 is increased without an equal increase in the side lobes.

The ψ metric is higher for S_2 after SSR-TRA of S_1, therefore the focus at S_2 is more clearly identified. Figure 5 displays ψ for the time reversed focal signals at S_1 and S_2 before and after performing the SSR-TRA method (subplot a.). Also plotted in Figure 5 is the ratio of ψ after SSR-TRA to ψ before source reduction, $\psi_{After}/\psi_{Before}$ for S_1 and S_2 (subplot b.). ψ for S_1 is always decreased after SSR-TRA of S_1, although the decrease in ψ does not correspond to decreasing the focus amplitude to the noise floor. It should be noted that both peaks in the time reversed focus at S_1 after SSR-TRA were considered part of the focus (thus neither was considered a side lobe) and the higher maximum amplitude of the two was used to compute the ψ. ψ for S_2 increases with the input source ratio up

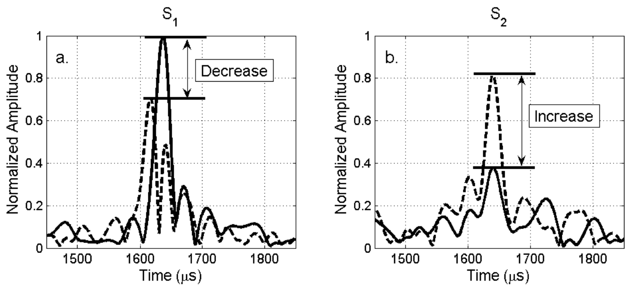

FIGURE 4. Time reversed focus plots demonstrating the selective source reduction method to reduce S_1 and reveal S_2. The subplots a. and b. are for an original source ratio of A_1/A_2 = 2.63. The subplot a. is for S_1 while subplot b. is for S_2. The solid lines represent the time reversed foci before and the dashed lines represent the time reversed foci after S_1 reduction.

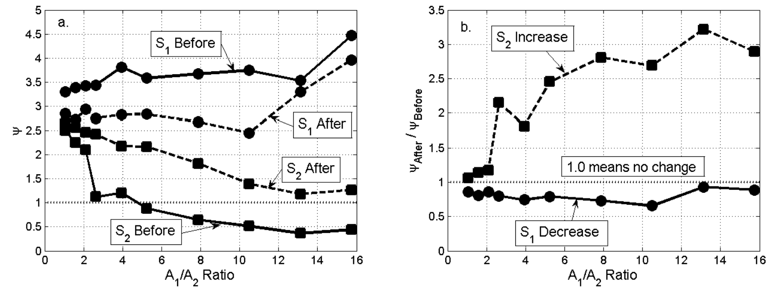

FIGURE 5: Subplot a.: Amplitude ratio of the peak of time reversed focus to the highest side lobe amplitude for S_1 and S_2 before and after S_1 reduction versus the original source ratio A_1/A_2. The lines with circles and the lines with squares represent the S_1 and S_2 time reversed focus quality, ψ, respectively. The solid and dashed lines represent ψ before S_1 reduction and after S_1 reduction, respectively. Subplot b.: Ratio, $\psi_{After}/\psi_{Before}$, change in the amplitude ratio of the peak of focus to the highest side lobe amplitude for S_1 and S_2 after S_1 reduction versus the original source ratio A_1/A_2. The ratio for S_1 and for S_2 are given by the solid and dashed lines respectively.

to a ratio of 13 and then it flattens out as the input ratio increases. The reason for the peak in $\psi_{After}/\psi_{Before}$ for S_2 at an input ratio of 2.63 is unknown. From the data displayed in Figure 5, it is apparent that the SSR-TRA method brings the focus at S_2 out of the side lobe noise floor at input amplitude ratios greater than about A_1/A_2 = 5. The improvement in ψ for S_2 after SSR-TRA of S_1 appears to reach an asymptotic value of about 3. At A_1/A_2 values of 13 and higher, it is apparent that the focus at S_2 is just above its side lobe noise floor, therefore we define a ratio of A_1/A_2 = 13 to be the limit for this specimen at which the focus at S_2 is no longer detectable after performing SSR-TRA on S_1.

DISCUSSION OF EXPERIMENTAL RESULTS

It has been shown that the time reversed focus of a dominant source may be reduced, thereby providing the means to detect a weaker source. The dominant source, S_1, is reduced in amplitude but a remnant of the focus is apparent after SSR-TRA of S_1. This remnant is due to an interference phenomenon. The first time reversed focus (solid line in the subplots of Figure 4) at S_1 is, ideally, a near perfect reconstruction of the original source function. However, in experimental studies, the focus is modified by the transducers' narrow-band response and is therefore not a near perfect reconstruction of the original source function. The transducers bonded to the sample have the effect of broadening the signal in time and it is common for the time reversed focus to be 3 times wider than the original source pulse as shown in Figure 6. This time broadening occurs as a result of ring down after the pulse has been transmitted or detected (the ring down frequency is the damped natural frequency of the transducer bonded to the sample). Thus, when the time reversed focus pulse is broadcast back into the medium, it is not the same as the original source broadcast from S_1. The forward direct arrivals and codas measured at the receivers will be different due to this difference. Therefore after subtraction of these forward signals, an interference remnant will remain which will give rise to two focal spots onto S_1 as shown in the dashed line in Figure 4a, corresponding to the differences in the reconstructed signal to the left and right of its maximum.

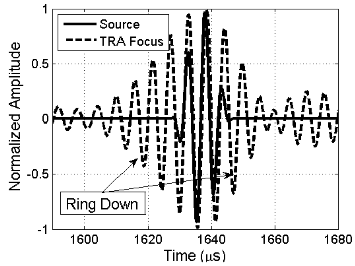

FIGURE 6: Comparison of the original input waveform (solid line) and the time reversed focus waveform (dashed line). Both waveforms are normalized to their respective peak envelope amplitudes. Note the broadening in time of the reconstructed source in the time reversed focal signal relative to the source pulse.

CONCLUSIONS

This paper has numerically and experimentally verified the Selective Source Reduction in Time Reversed Acoustics (SSR-TRA) method. It has been shown that a weaker source, which is masked by a stronger source, may be illuminated, by employing a method based on subtraction of the dominant source direct arrival and coda. As shown, the method proposed here is not limited by restrictive assumptions about the configuration of the system, nor does it require *a priori* knowledge about the sources to be detected. Furthermore, since it exploits the full coda, few transducers are required. The limitation of resolving only surface sources, can be overcome by performing the rebroadcast procedure in a numerical model of the sample, after the experimental data of the first forward propagation are given (so that sources in the interior may be imaged).

SSR-TRA is complementary to other approaches developed to obtain selective focusing using Time Reversal. In fact, to our knowledge, the existing approaches based on DORT (and its variations) [13-14] address the issue of selection of embedded targets, but are not applicable to primary source identification. To the authors' knowledge this method provides the only available method of resolving masked primary sources (or nonlinear scatterers) in a complex source problem without prior knowledge of the source function(s) and/or without modification of the sample. In a broader context, if multiple sources exist near a primary source time reversed focus, but their positions are unknown, iterative TRA at spatial locations near the time reversed focus may provide the means of locating them.

Though it has not been verified numerically or experimentally to date, we propose that SSR-TRA may be used to identify multiple cracks, which behave as nonlinear scatterers. Time Reversal and Nonlinear Elastic Wave Spectroscopy (TR-NEWS) may be used to locate nonlinear scatterers, but the spatial resolution limitations in TR-NEWS are the same limits inherent in standard TRA. Therefore it is conceivable that one may use SSR-TRA and TR-NEWS to locate individual cracks which are located in close proximity to each other, where their detailed structure is not resolved using TR-NEWS.

For the experimental sample used, this method allowed a weaker source to be illuminated, up to a limit of the stronger source having amplitude 13 times greater than the weaker source (10 times from the numerical data), though this limit is likely system dependent. This method provides a unique method to resolve two close proximity sources (diffraction limited) which cannot be resolved using standard TRA. The method is limited by the source reconstruction ability of the time reversed process, which greatly depends on the transducers used.

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