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Time reversal and non-linear elastic wave spectroscopy (TR NEWS) techniques

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Abstract

Non-linear elastic wave spectroscopy (NEWS) has been shown to exhibit a high degree of sensitivity to both distributed and isolated non-linear scatterers in solids. In the case of an isolated non-linear scatterer such as a crack, by combining the elastic energy localization of time reversal (TR) with NEWS, it is shown that one can isolate non-linear scatterers in solids. The experiments reviewed here present two distinct methods of combining TR and NEWS for this purpose. The techniques each have there own advantages and disadvantages, with respect to each other and other non-linear methods, which are discussed.

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Keywords: Time reversed acoustics; Non-linear elasticity, Imaging; Non-destructive evaluation; Crack characterization

1. Introduction

Combining the time reversal mirror (TRM) with elastic non-linearity holds great promise for isolating a non-linear scatterer such as a crack in a solid. The TRM provides the means to narrowly focus wave energy in time and space as well as the ability to focus acoustic energy on a scatterer without knowing its location *a priori* [1]. The focusing abilities of the TRM can be used in conjunction with non-linear elastic wave spectroscopy (NEWS) [2] to locate and image non-linear scatterers in an otherwise linearly elastic medium. To date, two such methods have been devised for combining time reversal (TR) and NEWS for this purpose. These two methods use TR and NEWS in distinctly different manners, essentially stemming from the use of what we refer to as the standard or reciprocal TR methods [3]. This paper will review the two techniques previously introduced by Ulrich et al. [4,5]. Additional results from both methods are shown as further validation of the methods.

To proceed with the distinction between the two methods, it is first necessary to clarify our use of the terms “standard TR” and “reciprocal TR”. In both standard and reciprocal TR the procedure involves first having an active source, $S_A(t)$. As this source emits (e.g., a single period of a sinusoid) at position A, an array of M detectors (i.e., the TRM) records the direct arrival and the scattered signals $R_M(t)$, at some other location(s). These signals are time reversed (i.e., $R_M(t) \rightarrow R_M(-t)$) and broadcast back into the system, thus producing a TR focused signal $F_X(t)$, where X denotes the spatial location of the focused signal. Fig. 1 displays waveforms resulting from this process for a single element TRM located at position B. The distinction between standard TR and reciprocal comes in the choice of location from which to broadcast the time reversed signals $R_M(-t)$. Standard TR requires that we broadcast from the original point of detection, thus focusing the energy back at the original source location A. In the case of reciprocal TR, the goal is not to focus energy back to the original source, but rather to focus energy at a point defined by the location of the detector, say location B. To do so, the signal $R_B(-t)$ must be broadcast from the original source location A. As spatial

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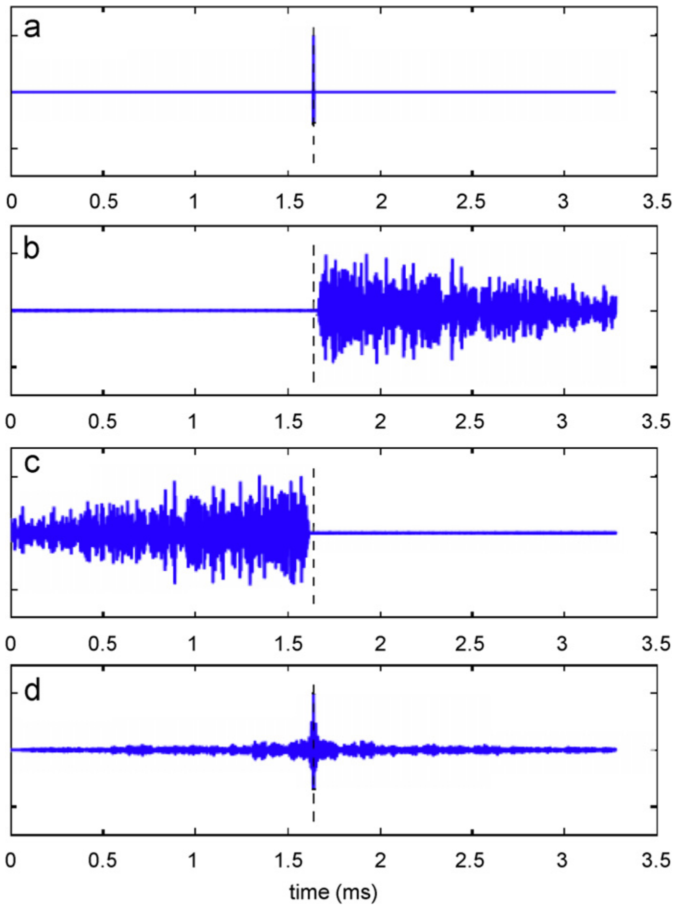

Fig. 1. Waveforms from the TR experiment: (a) input signal $S_A(t)$; (b) signal received at the point of detection $R_B(t)$; (c) TR signal $R_B(-t)$ input to the transducer; (d) focused signal $F_X(t)$ due to the transmission of the TR signals, i.e., (c). Note for standard TR, $X = A$; while for reciprocal TR, $X = B$. A vertical dashed line is shown in each panel to provide a reference for the original source time and/or expected focal time.

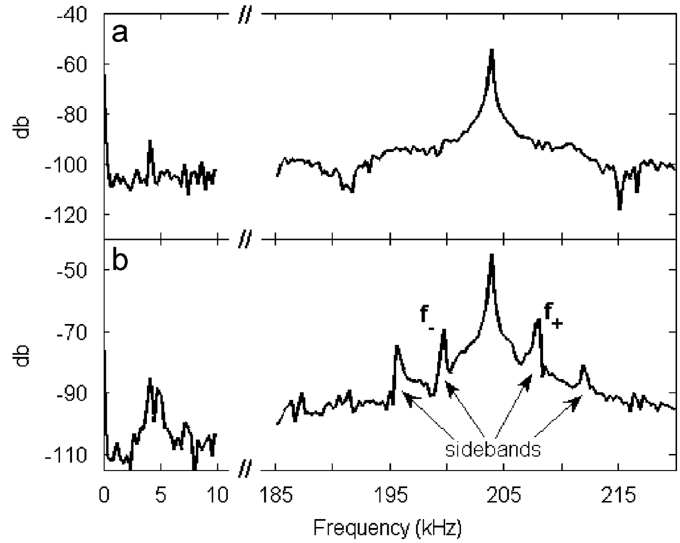

Fig. 2. (a) Power spectrum from an elastically linear (undamaged) sample (sample 3) indicating no wave mixing between the low and high frequency signals. (b) Power spectrum from an elastically non-linear (mechanically damaged) sample (sample 2) showing the mixing of a high frequency pure tone (204 kHz) with a low frequency (4 kHz) normal mode. The samples are identical (i.e., geometry, transducer locations, wave speed, etc.) with the exception of the presence of a ~ 1 cm crack in the non-linear sample.

reciprocity is already a cornerstone of the TR process, and must hold for TR to be successful, it is meaningless in the formalism to interchange the source and receiver positions; thus TR focusing still occurs, only now at the original detector location B. Now, to utilize either of these TR procedures for the use of locating and imaging non-linear elastic features (e.g., cracks, delaminations, disbonds), we must properly introduce NEWS.

NEWS is a set of techniques to determine the presence, and degree, of non-linearity in elastic systems. Non-linear elastic waves can be generated in a material due to a variety of reasons: anharmonicity of the interatomic potential, dislocation motion, contact mechanics, etc.; and can be present globally throughout the material or be highly localized. NEWS has been widely applied to many materials and for many purposes [6]. Here we are concerned with locating and imaging localized non-linear elastic features, thus we can narrowly limit our discussion of NEWS to elements relevant to fractures and similar features.

It is well known that fractures and delaminations are such features exhibiting elastic non-linearity, and thus producing additional frequency content, not present in the original source excitations. These "new" frequencies are those associated with the harmonic and/or intermodulation distortion that arises as elastic waves encounter the localized non-linear features (e.g., cracks). Exciting a sample with elastic waves for the purpose of looking for these "new" frequencies is known as non-linear wave modulation spectroscopy (NWMS) [2], one of many NEWS techniques. It is often realized through the application of a steady state continuous wave (CW) of a pure tone (i.e., single frequency) combined with a semi-broadband impulse (impact). This combination, in the presence of non-linear elasticity, produces a rich spectrum of frequencies. First, of course, the linear frequencies can be measured. These include the CW frequency, say f_1, and the low frequency vibrational modes of the object, excited by the impact, say f_2. Additionally the frequencies f_1 and f_2 will produce harmonics ($2f_1$, $3f_1$, $2f_2$, $3f_2$, etc.) and modulations ($f_1 \pm f_2$, $f_1 \pm 2f_2$, etc.) when they come together at the non-linear features. It is these frequencies that will be referred to as the non-linear frequencies. In Fig. 2 we can see the spectra resulting from performing this impact + CW style experiment on two identical samples, differing only in the presence of a 1 cm crack in one of the samples.

To find this kind of non-linear feature, such as is responsible for the mixing frequencies, ($f_\pm = f_1 \pm f_2$) we must now address the methods necessary to use either standard or reciprocal TR, separately. In the following sections each of these methods will be discussed and results presented before discussing advantages and disadvantages of one method over another.

2. Standard TR

In the above discussion on the TR process, one required element was the active source. In linear TR experiments, this

Table 1
Sample dimensions and descriptions

Sample no.	Dimensions (cm)			Description
	x	y	z	
1	6.5	3.5	0.5	Notched rectangular steel block, contains 1 cm crack extending downward in the y-dir, crack penetrates entirely through the sample (z-dir)
2	13.5	6.5	3.5	Gray iron automotive bearing cap, 1 cm "hair-line" crack extending from inner arch across surface (i.e., x–y plane), crack extends 0.5 cm into the sample (z-dir). See photograph in Fig. 2
3	13.5	6.5	3.5	Gray iron automotive bearing cap, identical to sample 2 without the crack. No non-linear scatterers present. Sample 3 used as linear comparison to sample 2

Table 2
Experimental parameters used for standard TR NEWS imaging experiments performed on the three individual samples

Sample no.	NL scatterer description	M (no. TRM elements)	N_x (no. steps)	N_y (no. steps)	ΔX (mm)	ΔY (mm)	f_{lo} (kHz)	f_{hi} (kHz)
1	1 cm crack	4	31	26	1	0.8	3.8	200
2	1 cm crack	6	25	25	1	0.8	4	204
3	None	6	25	25	1	0.8	4	204

active source can simply be a transducer excited with a function generator. In the non-linear case, the active (non-linear) sources for which we are searching are the cracks in our samples. The cracks must be stimulated with an external excitation, such as in the impact + CW style mentioned above, in order to actively generate the non-linear frequencies; thus becoming an active source of non-linear frequencies. The non-linear frequency components are then extracted from the signals measured by the TRM elements and broadcast (again, from the TRM itself) in order to focus back onto their original source, the crack.

2.1. Experimental details

The above scenario is realized experimentally in the following manner: the sample is excited from $t = 0$ simultaneously with a broadband impulse (which excites its low frequency normal modes, e.g., $f_2 = 4$ kHz) and a narrowband high frequency tone-burst (200 cycles at $f_1 = 204$ kHz). At the site of a non-linear scatterer in the sample the low frequency mode(s) and the high frequency tone-burst are mixed and broadcast at frequencies $f_\pm$ and possibly others. It is apparent that the source of the non-linear signals (i.e., $f_\pm$) is the crack when one compares the frequency spectra (Fig. 2) of two samples where the non-linear sample contains a crack, but is otherwise identical to the linear sample (e.g., samples 2 and 3 in Table 1).

Immediately upon exciting the sample, as described above, the elastic response of the sample is recorded at M different locations (TRM elements) on the sample surface using piezoelectric ceramic disks (PZT-5A, 1 cm diameter, 2 mm thick) bonded to the sample with epoxy (Devcon 2 ton). The signal recorded by each ceramic disk is Fourier analyzed to determine the spectral composition of the response, Fig. 2. Each of the M recorded signals is filtered about a frequency prominent in the response, i.e., $f_\pm$, time reversed and broadcast into the sample.

Following the broadcast of the time reversed filtered signals we detect the particle velocity on the surface of the sample, $U(x_{ij}, t)$ $(0 \leqslant t \leqslant \tau, x_{ij} = (x_0 + \mathrm{i}\Delta X, y_0 + \mathrm{j}\Delta Y), i = 1, \ldots, N_x, j = 1, \ldots, N_y)$ with a scanning laser vibrometer system (Polytec OFV303/3001, 125 mm/s/V). Typically in TR experiments, the source of the signal to be time reversed is sharply defined in time (e.g., a delta function or single period sinusoid). Here the source is of unknown temporal structure as it is due to the mixing of the two primary sources as they visit the site of the non-linear feature. Without knowledge of the form or timing of this source we can neither define an initial source time nor anticipate a time of focus. To overcome this difficulty we assume that the amount of energy delivered to a point x_{ij} on the surface, over the duration of the recorded focused signal, will be greatest at the spatial focal point. Using this assumption the x_{ij} with the largest value is the spatial focal point x_{foc} if the focal point lies with in the scan area. We calculate an energy from the surface velocity amplitudes $U(x_{ij}, t)$ using

$$E(x_{ij}) = \int_0^\tau U^2(x_{ij}, t)\,\mathrm{d}t, \tag{1}$$

with the total duration of the signals $U(x_{ij}, t)$ being τ. The primary data reported are $E(x_{ij})$.

Results from three samples will be described herein. Sample designations and descriptions can be found in Table 1, while the experimental parameters are listed in Table 2. Two of these samples (1 and 2) contain non-linear scatterers (cracks) while the third is used to compare the results of the process in a linear sample (i.e., no crack present). With the exception of the presence of the crack in sample 2, samples 2 and 3 are otherwise identical (including transducer placement). The non-linear scatterers in samples 1 and 2 exhibit a known surface expression, allowing us to define an appropriate set of x_{ij}'s as the scan area in which to conduct the experiments.

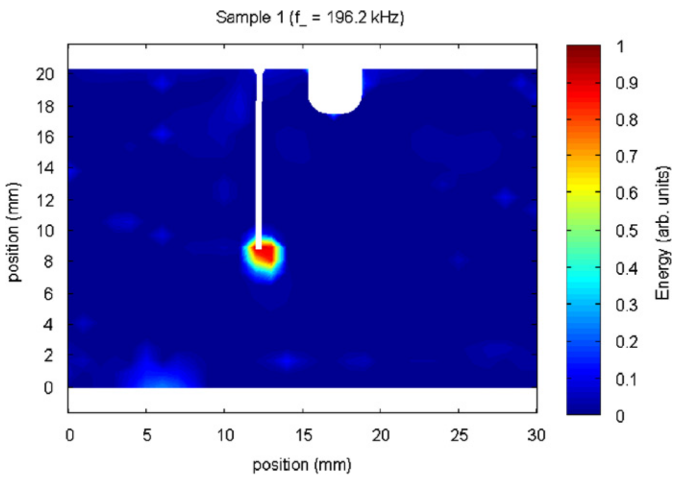

Fig. 3. Elastic energy (as calculated from Eq. (1)) localization in the elastically non-linear sample from broadcasting the time reversed signal filtered about $f_- = 196$ kHz. The approximate extent of the crack highlighted in white has been over-layed to show its location. The U-shaped notch is also shown in white and is used to align the scan results with the scan area on the sample. Notice the large elastic energy localization at the crack tip.

2.2. Results

2.2.1. Sample 1

Performing the described experiment on sample 1 and creating a two-dimensional contour plot of the $E(x_{ij})$ results in the image shown in Fig. 3. Here the difference frequency ($f_- = 196$ kHz) was filtered from the direct signals $R_M(t)$ before being time reversed and rebroadcast. Clearly the hypothesis that the largest values of $E(x_{ij})$ will appear at the location of the non-linear scatterer is valid, as the time reversed focused signals are greatest at the crack tip. The fact that only the crack tip is illuminated is not entirely surprising as a similar phenomenon has been seen in other studies [7], and crack tips are known to be areas of high stress concentration, which may play a role in the source of non-linear elasticity.

2.2.2. Samples 2 and 3

Samples 2 and 3 are nominally identical samples, same geometry, wavespeed ($v = 3325$ m/s), and employing identical transducers identically situated. The samples differed in that #2 had a surface-intersecting crack that we explore. In Fig. 4 we show the rebroadcast signals detected by the laser vibrometer in the vicinity of the crack, integrated as in Eq. (1) over 3.277 ms following the initial TR broadcast. Fig. 4(a) and (b) are the results for sample 2. Shown in (a) and (b) are results for two different sideband frequencies. In Fig. 4(c) we show the result from performing the identical scan region of the linear elastic (undamaged) sample (sample 3). For re-broadcast at $f_+ \approx 208$ kHz (a) and at $f_- \approx 200$ kHz (b) there is energy focusing near the crack. This is in contrast to using a time reversed signal filtered about $f = 208$ kHz in the linear sample, which shows no evidence of such focusing.

It is interesting to note that in sample 2, the sum and difference frequencies appear to have different focal characteristics, i.e., the result of using f_+ appears to focus the energy at the crack opening (the end of the crack exposed to the arched free boundary) while the use of f_- indicates that some elastic energy is focused at the crack tip with most of

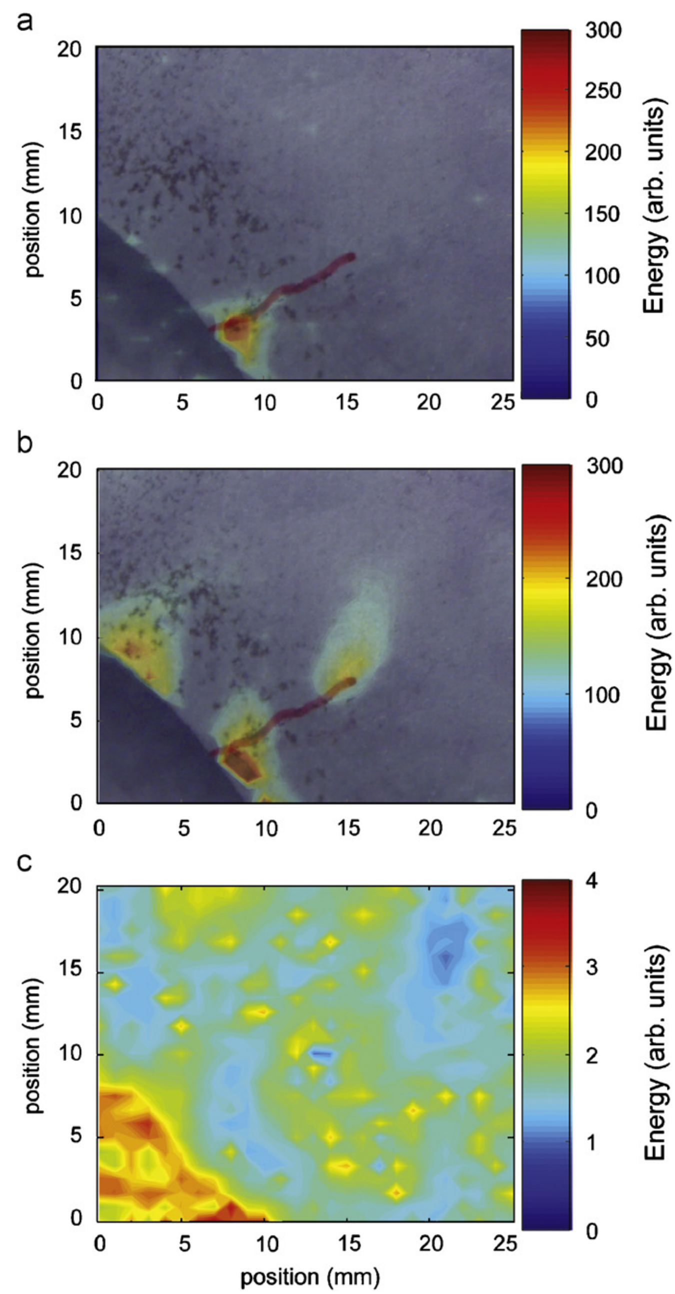

Fig. 4. Elastic energy (as calculated from Eq. (1)) localization in the elastically non-linear sample from broadcasting the time reversed signal filtered about (a) $f_+ = 208$ kHz, (b) $f_- = 200$ kHz (sample 2), and (c) $f_+ = 208$ kHz (sample 3). A photograph containing the crack in sample 2 has been over-layed to show its location in (a) and (b). Notice the difference in spatial focusing of the elastic energy depending on the sideband frequency used. (c) For comparison, the energy in an elastically linear sample is shown when filtering for $f_+ = 208$ kHz in the time reversed signal. Note the lack of focusing of energy, emphasized by the smaller energy-scale interval in comparison to both (a) and (b). The curved feature in the lower left portion of (a), (b), (c) is the arched boundary of the sample.

the energy focused at the crack opening as before. Each of these cases differ from the focusing characteristics seen in sample 1; that being elastic energy focalization only at the crack tip. The reasons for the differences seen in focusing due to different frequencies or different samples are poorly understood. Additional work is required to explain these phenomena.

This work illustrates that a non-linear scatterer can be isolated applying the TR NEWS method illustrated here. Similar analysis methods can provide images of the spatial and temporal complexity [5]. Here we are able to explore the spatial–temporal nature of non-linear scattering from a mechanical damage feature. This interrogation of the dynamical response of a non-linear feature to an elastic wave may provide the details necessary to construct constitutive models of crack/wave interactions. The source of non-linear elasticity in mechanically damaged samples has been speculated to arise from asperity friction, crack "clapping", thermo-elasticity, dislocation-point defect interaction, adhesion due to fluids, and possibly others. The method presented here may provide the means to support or dispute the above speculations or even spawn others. These are open questions we intend to explore in order to further understand the physical basis of the origins of non-linear scattering in such a system.

Another goal of this research is remote imaging of isolated non-linear scatterers. That is, here we directly image the surface of the sample over the region of the scatterer because we know where it is located and are able to directly access the feature at the surface of the sample. An internal scatterer located at an unknown position presents a more difficult problem. Our approach to this problem is to make the same lab measurement presented here, but back-propagate the filtered, time-reversed signal numerically in order to locate and image the internal non-linear scatterer. This technique would require an experimentally obtained material velocity structure (i.e., travel time tomography), the direct signals $R_M(t)$ described herein, and a numerical model capable of properly utilizing the afore mentioned experimental data. Work is currently being conducted to utilize the LISA model [8,9] for this purpose.

3. Reciprocal TR

Here we utilize the spatial and temporal focusing abilities of TR to produce a large amplitude response at a highly localized, and user defined, point in time and space. This is done by utilizing reciprocal TR to focus the elastic energy at the location of the detector, positioned by the user. In the cases shown, that detector is a scanning laser vibrometer, as was used for the standard TR experiments. This allows for the ease and speed of moving the detector location (B) in order to determine the presence of a non-linear feature in a large region. Combining reciprocal TR and NEWS in the manner discussed below is a technique termed TREND (i.e., time reversal elastic non-linearity diagnostic).

3.1. Experimental details

In the glass block and diffusion bonded samples used for these studies, the general TR procedure outlined in the Introduction, and illustrated in Fig. 1, was used. In order to have multiple source functions (i.e., N narrow frequency band sources), the samples were fitted with $N = 2$ source transducers. Each transducer was used independently (i.e., with the other transducer inactive) as a source, and the resulting $R_N(t)$ recorded and time reversed. Note that the subscript on R now denotes the source used. As an R_N is measured for each source at a single detector location, the reciprocal TR process can be done for each source. Individually this has little value, however, if all of the $R_N(-t)$ are properly synced and broadcast simultaneously from their respective sources, the result will be an increase in the strength of the focus by a factor N; thus by adding more sources the ability to obtain large amplitudes rises quickly. As the non-linear response of a material is amplitude dependent, the large increase in amplitude at the focal point is highly desirable and advantageous to determining the presence of non-linear features. Finally, the N source functions can be defined having different frequency content. Here the two source functions were defined with differing narrow frequency bands (f_1 and f_2) so as to employ NWMS to distinguish non-linear features from the linear background. Thus, the combination of illuminating non-linear features by applying TR and analyzing the focused signal for a non-linear response as a function of detector position, offers the means to image them. Other wave scatterers such as sidewalls and voids do not exhibit a non-linear response [10]. Here we show how the method can be applied to provide an image of a crack located on the surface or near the surface of a glass block. Also included is the resulting image from performing the method on a pair of diffusion bonded samples having variable bond quality.

3.1.1. Glass block

The first experiment was conducted in a doped glass block of dimensions $101 \times 89 \times 89$ mm ($\rho \sim 3.0\,\mathrm{g/cm^3}$, $c \sim 2.5\,\mathrm{km/s}$, $Q \sim 2000$). Two piezoelectric ceramics (PZT-5A, 38 mm diameter, 2.8 mm thickness) were used as sources ($f_1 = 255$ kHz, $f_2 = 170$ kHz). The sources were bonded to the face of the glass block opposite to the crack location. The elastic response on the cracked face was measured using a broadband (DC to 1.5 MHz) laser vibrometer (Polytec model OFV 303, controller OFV 3001, velocity range 1 V = 1 m/s). In these experiments we restrict ourselves to focusing on the surface of the sample; as such, the crack analyzed here is a surface crack with a penetration depth of a few millimeters.

3.1.2. Metallic disks

Three samples were examined. Each sample measured approximately 70 mm in diameter and 7 mm in thickness, and were composed of two dissimilar metal disks (diameter = 70 mm, thickness = 3.5 mm), stacked, welded

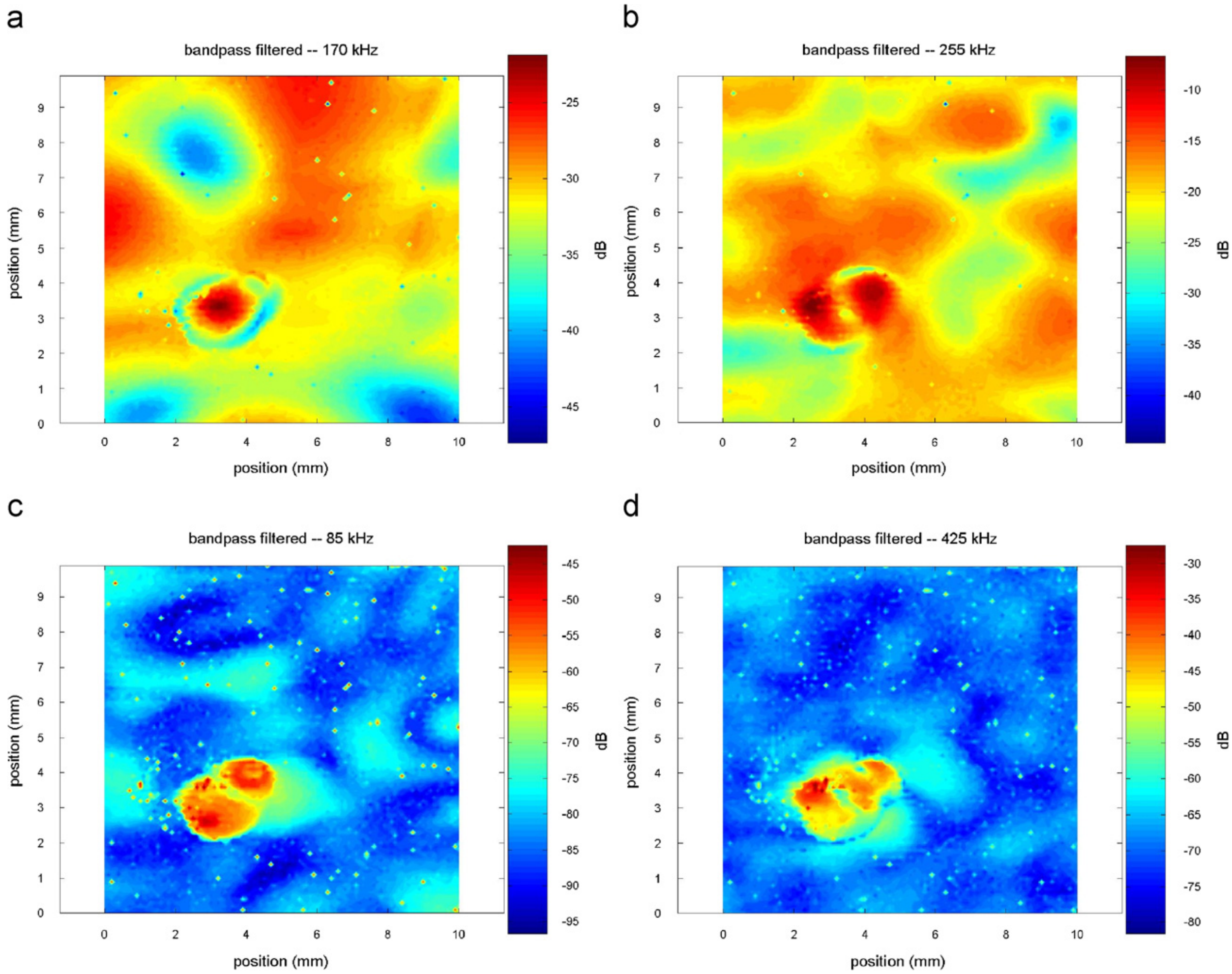

Fig. 5. A two-dimensional TREND scan be performed in the glass block. Top: the linear response (f_1, a; f_2, b) in the scan area. Bottom: the non-linear response (f_-, c; f_+, d) in the scan area. The images are constructed by first band-pass filtering the focused signals about the desired frequency, and then extracting the maximum amplitude of the filtered signals at each scan point. Note the greatly increased contrast of the cracked region from the surrounding intact material in the non-linear response images (bottom panels).

and diffusion bonded. The preparation for the diffusion bonding process require the two metallic disks be machined flat and welded around the outer edge prior to entering the high temperature and pressure apparatus used to achieve a diffusion bond between the two disks. Two samples were diffusion bonded, each under different conditions having a potential to produce poor quality bonds.[1] The third sample was identically prepared (i.e., identical materials, machining procedure, and welding) but was not put through the diffusion bonding process.

Two PZT-5A transducers were affixed to each sample. The frequencies used to obtain a non-linear wave mixing were $f_1 = 4$ kHz and $f_2 = 200$ kHz. The scanning procedure was performed with a 3 mm step size in both the X and Y directions, and the same laser vibrometer used in the previous experiments was used to measure out of plane velocities at each scan point.

[1] Proprietary information prevents further description of the two dissimilar metals and the diffusion bonding conditions used.

3.2. Results

3.2.1. Glass block

In Fig. 5, the results of a two-dimensional scan performed in a region containing a crack, are found. To create the images the focal signals recorded at each scan position are band-pass filtered. The maximum amplitude from these filtered signals are then extracted at the focal time and plotted as a function of focal position. Displayed is a comparison of the linear response (top panels) of the scan area to the non-linear response (bottom panels). Here it is abundantly clear that the non-linear response provides an increased contrast for distinguishing the crack from the surrounding intact material.

It is also apparent that the sum and difference frequencies are not identical in behavior, i.e., the difference frequency f_- is relatively constant in the damaged region (Fig. 5), while the sum frequency f_+ is only seen in one portion of the crack. The differences between the different non-linear frequencies may provide the ability to characterize the crack. We speculate that

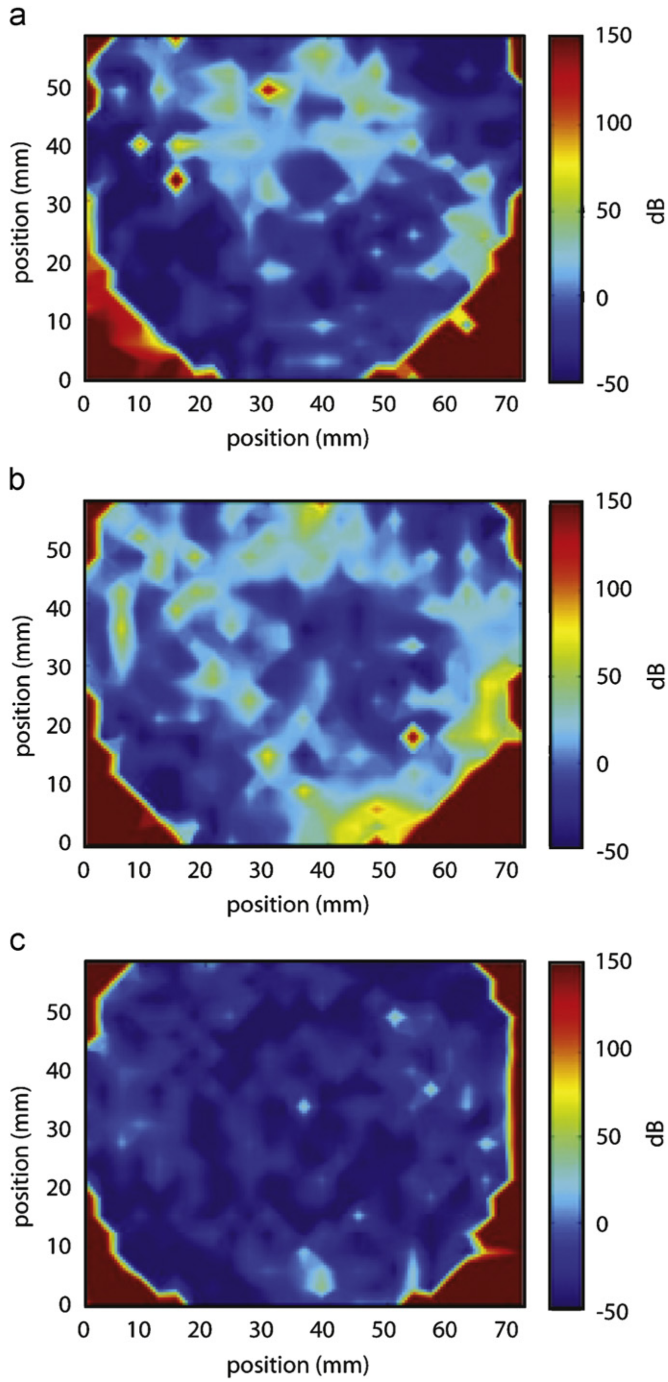

Fig. 6. Two-dimensional scans performed on three metallic disks: (a) and (b) are diffusion bonded samples, whereas (c) depicts the results from the welded sample. The non-linear response (f_-, f_+, etc.) in the scan area. The images are constructed by first band-stop filtering the focused signals to eliminate the linear response (i.e., f_1 and f_2), then extracting the maximum amplitude of the filtered signals at each scan point. The hypothesis is that the localized non-linear responses in the diffusion bonded samples are areas of poor bonding. Work is being conducted to confirm this and determine local bond strength through destructive testing.

the difference in wavelengths of the non-linear frequencies may be used to provide information about the penetration depth in different portions of the crack, however, this analysis has yet to be done.

3.2.2. Metallic disks

Results of the TREND experiments on the metallic disk samples are shown in Fig. 6. The images were constructed by using the cumulative non-linear response, i.e., all of the non-linear frequencies present in the focused signals, rather than separating each non-linear frequency as was done for the glass block images above. This cumulative non-linear response is obtained by band-stop filtering the linear input frequencies. An identical image can be obtained by filtering for the most prominent non-linear frequencies and adding each of the resulting images to obtain one image.

The welded sample (Fig. 6(c)) shows the least non-linear response of the samples. The welding process involves only the edges of the disk, leaving contact area between the two metal disks as a rigid interface. This interface is a linear feature at the drive amplitudes ($A < 100$ V) used in these experiments. In contrast to the welded sample, the two diffusion bonded samples exhibit localized areas of non-linear elasticity, presumably at weakly bonded areas. These preliminary results illustrate the ability of the TREND method to detect and locate areas of poor bonding in diffusion bonded metals. Further destructive tests are being conducted to verify the localized bond quality and determine the associated bond strength.

4. Discussion

The interaction physics of an elastic wave with a non-linear scatterer in a solid is a fascinating and extremely complex process. The scattering process induces localized wave distortion and simultaneous non-linear wave mixing, producing wave harmonics and intermodulation [11]. A non-linear scatterer could be localized, e.g., a crack, a delamination, thermal damage in an otherwise elastically linear material. It could be present uniformly in a material having distributed non-linear scatterers, such as in a rock sample, some ceramics and some metals [11,12]. The presence of non-linear scattering is an extremely sensitive diagnostic for the presence of mechanical damage [2,12,13]. However, few measurements exist that directly image the non-linear scatterer or see the dynamics of the scattering process. Such measurements are difficult to conduct. One of the few examples is Kazakov et al. [7] in which the geometry of the sample, a thin metal plate, allowed one to "image" a crack. These authors found significant non-linear scattering near the crack center and at the crack tips. Solodov et al. have also used non-linear elasticity for imaging delaminations in thin composite plates, for example [13]. Both of these methods require that the entire sample be excited with large amplitudes. In contrast, TR provides the ability to excite regions of a sample with large amplitudes, leaving other areas relatively unperturbed. This spatial focusing ability can be used to advantage by allowing the use of focal amplitudes that are not attainable from the same equipment (i.e., generator and amplifier) when operated in a CW mode, for example. Further, by exciting smaller regions of a sample it is less likely that a non-linear feature outside of the region of interest will be detected, both an advantage and disadvantage depending upon the user's goal. All of these methods currently only allow for the imaging of surface and near-surface features (near surface being defined by the diffraction limit of the frequencies used).

Unraveling a crack's behavior will require experimental probes that can directly and actively disturb it and watch its response. The experiments reported here, combining standard TR and non-linear scattering, is a first step in this direction. The following method differs from the TREND method by utilizing the ability of TR to refocus energy onto an unknown source (i.e., unknown location and unknown time structure), rather than the ability to localize a well-known source onto a user defined position. Furthermore, the afore mentioned method (TREND) uses the focused signal to induce a localized non-linearity, while the standard TR NEWS method time reverses and broadcasts the non-linear component(s) of a signal to locate a non-linear source/scatterer. Experimentally speaking, the standard TR method is much less intensive, as the initial forward signals must only be measured once in order to extract the non-linear components. TREND, on the other hand, requires possibly hundreds or thousands of measurements (i.e., no. of sources $*$ no. of scan points $=$ no. of measurements). However, the resulting focal signals from TREND are nearly trivial to analyze and use to create images. Further, the limitation of TREND to only image surface features is not strictly true for the use of standard TR and NEWS. It is true that to experimentally verify the validity of standard TR NEWS, the feature must be on or near the surface, however, through the use of numerical models it is theoretically possible to use standard TR with non-linear signals to locate buried features.

In summary, this work indicates that the spatial and temporal focusing abilities of TR can be complemented by the sensitivity of non-linear elastic measurements to the presence of damage. Using these two techniques together in one of the manners described here, provides a means to detect and image damage, and potentially other non-linear features. The choice of which non-linear elastic technique to use, TR based or not, will ultimately depend on the needs of the user.

Acknowledgments

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