A high amplitude, time reversal acoustic non-contact excitation (trance)

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Abstract: This paper describes the principle behind a high amplitude non-contact acoustic source based on the principle of time reversal (TR), a process to focus energy at a point in space. By doing the TR in an air filled, hollow cavity and using a laser vibrometer in the calibration of the system, a non-contact source may be created. This source is proven to be more energetic than an off the shelf focused ultrasound transducer. A scaled up version of the proposed source has the potential to allow nondestructive evaluation processes that require high amplitude, such as nonlinear elastic wave spectroscopy (NEWS) techniques.

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1. Introduction

During the last few decades, nonlinear acoustic techniques have been developed to detect mechanical damage in solids.[1–4] They have been proven to be far more sensitive to early damage than standard linear acoustic techniques such as C-scans, time of flight, etc. Unfortunately, nonlinear techniques often require high amplitude waves to be generated within the sample. Achieving such high amplitude is a challenge and often requires the bonding of transducers to the sample under study, reducing the field of application and the practicality of such methods for the industry. To allow fast measurements, one would like to be able to generate waves in a sample without touching it. This would also improve the reproducibility and thus the reliability of tests as the bonding quality is always an issue in nonlinear measurements. To date, non-contact acoustic transducers are not efficient enough to be use for nonlinear techniques. Here we propose a new source that could generate high amplitudes without contact via air coupling. We will first introduce the principles behind our new emitter, then describe the actual setup, and finally show the preliminary results obtained with our system. Note that the results presented here are not at amplitudes sufficient to excite nonlinearities in a sample, but they do show the potential to generate higher amplitudes, whereas currently available non-contact sources do not. The purpose of this paper is to demonstrate a new type of non-contact source that excites vibration amplitudes on a sample with higher spatial resolution and higher amplitudes than a commonly used commercially available focused ultrasound transducer source.

2. The principles behind the concept

This emitter is based on the principle of time reversal (TR). TR is a way of focusing energy.[5,6] The version we use is based both on the reciprocity principle and on the invariance of the wave equation with the sign of the time variable (see example from previous work on solids in Fig. 1). In traditional TR, a wave is sent from point A to point B where it is recorded. This signal is called the direct signal. If this direct signal is flipped in time and broadcast from point B, the invariance of the wave equation

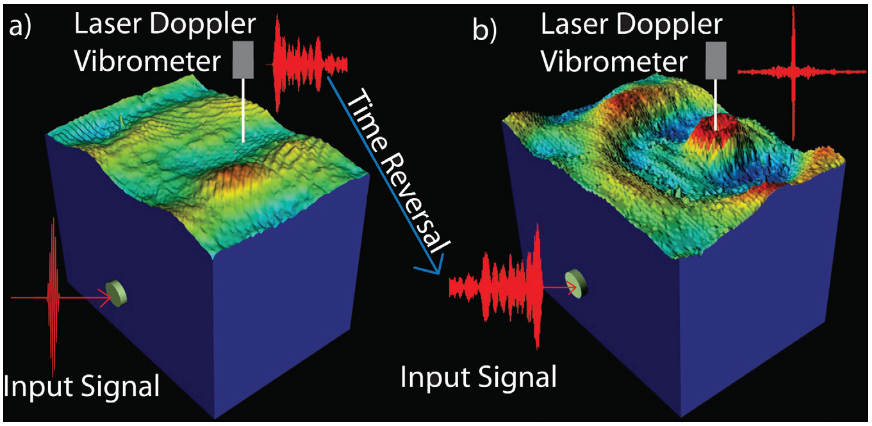

Fig. 1. Basic steps for focusing energy using time reversal (TR). For this illustration of TR, from a previously reported experiment, let us consider a solid with one transducer on a side; the surface of the solid is scanned at several grid points using a scanning laser vibrometer to visualize the wave field. Step 1: A small short-duration signal is emitted from the input source (a), scatters around the sample, and is recorded at the desired point using a non-contact, laser Doppler vibrometer. Step 2: That signal is time reversed (i.e., flipped in time), amplified and, as shown in (b), emitted from the original source. The signal focuses at the desired point. While the experiment described in the preceding text was conducted in a solid sample, TR works in an analogous manner in an air filled cavity.

implies that the wave field will coalesce at point A where the signal that was originally emitted will be recreated. However, the reciprocity principle allows us to broadcast the time reversed signal from point A and thus create at point B, the desired focal point, which is an identical signal to the one that would be sent from point B to focus at point A. Of course, attenuation dictates that if we send the time reversed signal without any scaling, the signal detected in point B will be smaller in amplitude than the original signal. The key is that most transducers are limited in the amplitude of the signals they can generate. Here, thanks to energy conservation, if the time reversed signal is scaled in such a way that its maximum amplitude is the same as the one of the original signal, when the wave field coalesces at the point of focus, it will be of larger amplitude than what one was able to create directly from the transducer with the same amplifier. Indeed, all the energy contained in the long duration scattered signal collapses onto the highly localized (in time and space) focal point, making the TR process extremely efficient. The amplitude of the focus also scales linearly with the number of transducers, thus increasing from one to N transducers, increases the focal amplitude by a factor N.

TR is more efficient if the whole wave field can be recorded, time reversed, and broadcast. Here we use only one compressional transducer for each broadcast, thus missing some information. One way to improve the efficiency of the TR process is to have a system with some internal scattering;[7,8] the scattered waves recover information from directions other than just the direct path between the transducers.

To make our system sample independent, we tried to have most of the scattering occur in a closed canister with a hole at the bottom to allow the sound waves to reach the sample. Accordingly the direct signals are only dependent on the distance between this hole and the sample. For different standoff distances, a new set of direct signals would need to be acquired during a calibration step.

The emitter we describe here is composed of a hollow cavity covered with transducers. These transducers are used only as emitters. The acquisition of the direct signals is done via an out-of-plane laser vibrometer (here a Polytec OFV-303 vibrometer with VD-02 decoder) to avoid any contact between this system and the target object. A detailed description is given in the next section.

3. Description of the apparatus

The apparatus is composed of two main parts: The source, a cavity covered with transducers, and the electronics driving the transducers. The source, shown in Fig. 2, is a metallic hollow cavity. Eight piezoelectric (PZT) disks (25.4 mm diameter and 6.35 mm thickness) are glued to the inner walls of the cavity. For ease of construction, the cavity of this first proof of concept experiment is of pyramidal shape; it is composed of steel walls of 1.5 mm thickness. The base of the pyramid is a square of 10 cm, and the height of the pyramid is 10 cm. The cavity has two holes to allow a laser vibrometer to shine through the cavity to the focal point of our system on the sample under test. The hole at the base of the pyramid is circular and 16 mm in diameter; the one at the top, where the sound waves escape to the sample, is a square of 37 mm side length. Some studies to optimize the shape of the cavity are underway, and the results will be published in following papers. The PZT transducers are powered by a 12 bit Gage CompuGen 8150 board ($\pm$1 V output) and Tegam model 2350 power amplifiers (50 times gain). The desired signal is successively broadcast from each of the PZT transducers, and the direct signals at the synchronized focal point are recorded via the laser vibrometer on one of the inputs of a 14 bit Gage CompuScope 14200 card. The recorded signals are then time reversed and broadcast simultaneously by their respective PZT transducers.

A comparison between our system and a commercial off-the-shelf focused ultrasound transducer (FUT) (Model No. NCG50-D50-P150 from the Ultran group) was made. This transducer was chosen as it is 7.7 cm in diameter and 5.5 cm height. Adding the 15 cm standoff distance to this, the volume necessary for the two systems on top of the sample to realize and acquisition is similar. We used each system in the conditions where it can produce its maximum amplitude. For our source, we used a pulse signal spanning 50–100 kHz centered on the 75 kHz resonance frequency of the PZT transducers with a standoff distance of 3 mm. For the FUT, we used a sinusoidal pulse centered on its 50 kHz central frequency (the pulse had a bandwidth of 50 kHz) with its specified standoff distance of 150 mm. In both cases, the original signal was a short burst of a few cycles of a sinusoid. To ensure that there was no structural transmission path between the proposed source and the plate (or between the FUT and the plate), the experiment was setup on two floating vibration isolation tables (Newport LW3048B tables) with the proposed emitter on one table and the plate on the other. Two things are important in creating a good emitter: The extent of the region excited on the sample and the fidelity in creating the input signal. To test the former, we repeatedly emit the signal from our system and from the standard FUT to produce focusing on a thin plate of aluminum (0.45 mm

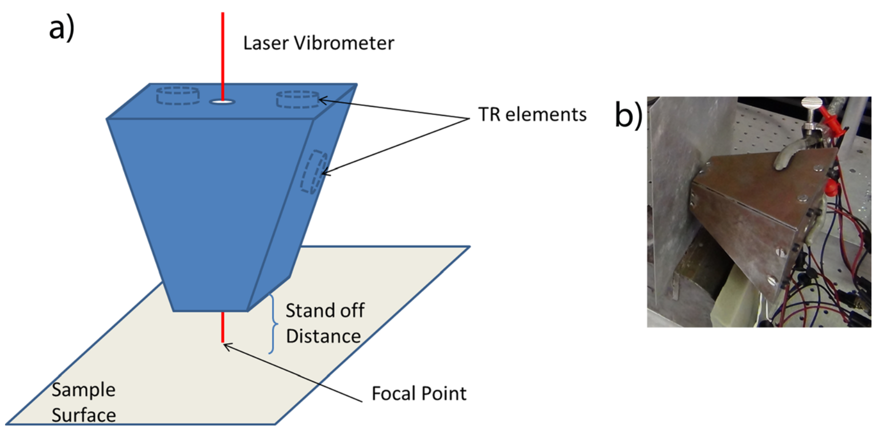

Fig. 2. (Color online) (a) Schematic drawing of the cavity: Transducers (bare PZT disks) are glued on a hollow metallic cavity. Two holes in the cavity allows the laser beam to go through and the sound to reach the sample at the focal point. (b) Cavity used to obtain the results in Fig. 3, there is a 3 mm gap between the cavity and the sample. Studies to optimize the shape of the cavity are underway.

thickness). We then scan the other side of the plate with a scanning system for our laser vibrometer. We scan the back side of the plate to demonstrate the spatial extent of the focusing on the plate. The thickness of the plate and the frequencies employed principally result in bending waves (anti-symmetric Lamb waves) in the plate with the vibration on the front side of the plate at any given point being the same as that on the back side, only with the opposite phase. The spatial focusing results are shown in Figs. 3(a) and 3(b). Clearly, our system has higher spatial resolution even when accounting for the difference in wavelength due to the use of different frequencies. For ease of comparison, the spatial dimensions in those figures have been normed by the wavelength associated with the center frequency used for each type of source. The spatial extent of the FUT focus is approximately 5 wavelengths (measured from null to null), whereas the spatial extent of the proposed source's focus is approximately a wavelength in size. If we now look at the temporal fidelity of the signal at the focus point [displayed in Figs. 3(d) and 3(e)], we can see some advantages and a couple weaknesses of our system. Note that the noise floor of the laser vibrometer is approximately 0.01 mm/s. Also note that the beginning of the emitted pulse for the FUT was at time 1000 μs. The weaknesses of the proposed source in comparison to the FUT include the fact that the signal is affected by a time reversal artifact known as side lobes (energy before and after the main focal pulse) and by the narrow bandwidth nature of the transducers used for the proposed source (note the wider temporal pulse created by the proposed source [Fig. 3(h)] compared to the width of the pulse created by the FUT [Fig. 3(g)]). One advantage is that there is only one distinct large amplitude pulse of energy from the proposed source (at 3276.8 μs), whereas the FUT

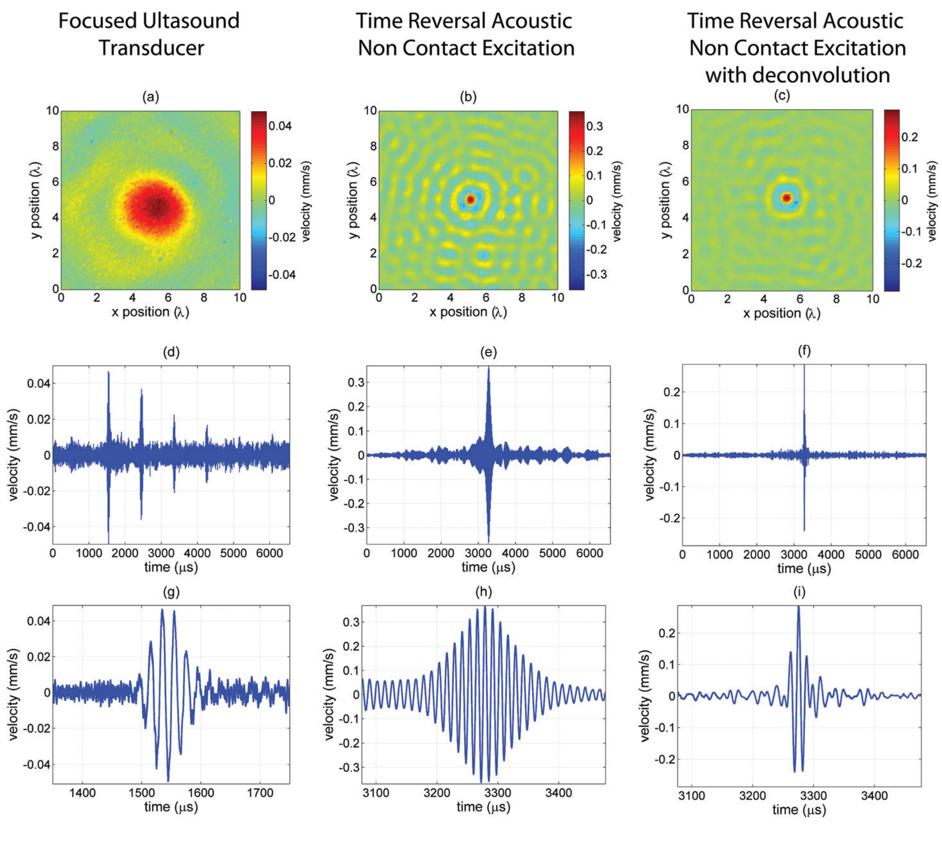

Fig. 3. Comparison between a focused ultrasound transducer (left), the time reversed acoustic non contact excitation (middle) and the time reversed acoustic non contact excitation using the deconvolution operation: Spatial extend in term of wavelength (a)—(c), signal generated in the sample (d)—(f), zoom of the main excitation signal generated in the sample (g)—(i).

repeatedly produces pulses of energy in the plate [four distinct pulses are apparent in Fig. 3(d) due to repeated reflections between the plate surface and the FUT surface, as the timing between successive pulses matches the estimated time of flight for two times the standoff distance]. However, the biggest advantage of the proposed system is that the achieved amplitude is much larger (about eight times). Thus each PZT transducer used in conjunction with the TR process achieves the same efficiency as the FUT considered here. This means that the proposed source can more easily be used for generating harmonics or wave mixing in a nonlinear system, particularly if more PZT transducers are used in the TR process. To improve the fidelity of the signal generated by the TRANCE, we can use the deconvolution method.[9] The result using this signal processing technique are shown in Figs. 3(c), 3(f), and 3(i). As can be seen, the results are much cleaner and show a good fidelity to the source signal. However, the amplitude is smaller because the deconvolution process utilizes some of the energy to interfere destructively with some of the time reversal side lobes. Nonetheless, the amplitude is still five times higher than with the FUT.

4. Conclusion

A non-contact source that exploits the efficiency of TR focusing has been demonstrated. The first results obtained with our non-contact emitter are promising. The amplitude and the spatial extent of the generated focal signal are better than those generated by a standard focused ultrasound transducer. The proposed source does avoid repeated reflections of energy between the source and the sample (as is a common problem for commercial focused ultrasound transducers). Future work includes building a new version with various sizes of PZTs that should allow increasing the bandwidth. Another feature of the proposed source that will be presented in a later communication when enough tests will be done is the ability to focus energy along different vector components, allowing even in-plane motion generation using a feature of time reversal presented in Ref. 10.

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