Proceedings of Meetings on Acoustics

Volume 19, 2013 http://acousticalsociety.org/

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Structural Acoustics and Vibration
Session 4pSA: Applications in Structural Acoustics and Vibration III

4pSA6. Imaging crack orientation using the time reversed elastic nonlinearity diagnostic with three component time reversal

Brian E. Anderson*, T. J. Ulrich and Pierre-Yves Le Bas

***Corresponding author's address: Geophysics Group (EES-17), Los Alamos National Laboratory, MS D446, Los Alamos, New Mexico 87545, bea@lanl.gov**

The time reversed elastic nonlinearity diagnostic (TREND) is a method to allow one to nondestructively evaluate a sample by locating nonlinear scatterers. In the TREND method one creates a localized focus of energy using time reversal at each point of interest. The localized nature of the focus, which is at a higher energy level relative to the wave field nearby thereby amplifying the potential nonlinear signature of the focal location, allows one to image localized nonlinearities. It has also been shown that a focus of energy may be individually created in each of the three independent vector components of vibration using time reversal. Here we show that the use of TREND scans in each of the three vector component directions allows imaging of a crack's orientation. This work is conducted on steel samples, each with cracks at known orientations that were created in a controlled manner. The scaling subtraction method is also used at each scan point to classify the nonlinearity. [This work was supported by the U.S. Dept. of Energy, Fuel Cycle R&D, Used Fuel Disposition (Storage) campaign]

Published by the Acoustical Society of America through the American Institute of Physics

Received 16 Jan 2013; published 2 Jun 2013

INTRODUCTION

The time reversed elastic nonlinearity diagnostic (TREND) is a time reversal (TR) technique that allows one to focus elastic energy to a particular evaluation point on a sample to inspect that point's nonlinear behavior.[1] Since TR provides a sharp focusing of energy to a particular point in space,[2-3] and therefore at a higher amplitude than the surrounding area, we can assume that any nonlinearity signatures found in the focal signal recorded at the focal point in space pertain mainly to the local region surrounding the focal point.

In a typical implementation of TREND one might bond, N, piezoelectric transducers to the sample under test and utilize a laser vibrometer to inspect the sample. First a source signal (that one desires to approximately recreate as a focal signal), S, is emitted from a single piezoelectric transducer (numbered as transducer number i). The laser vibrometer then records the *forward* vibration response of the sample at a point of interest, $R_i(x,y,t)$. This is repeated for each of the N transducers. The forward signals are then reversed in time $R_i(x,y,t) \rightarrow R_i(x,y,-t)$ and the reversed signals are then simultaneously emitted from the respective transducers from which they were originally emitted. If there is a sufficient degree of scattering of energy within the sample then each of the so called *backward* $R_i(x,y,-t)$ signals independently produces a focus of energy at the laser vibrometer position and they coherently add together. One can then use any one of several techniques to detect nonlinear signatures (e.g. looking for harmonic frequencies or sum and difference frequencies). This entire process (forward and backward emissions) is then repeated at each point of interest on a sample's surface. Signatures of nonlinearity at specific locations can indicate locations of cracking or disbonding.[4]

Ulrich *et al*. showed that one may utilize an out of plane laser vibrometer to focus energy mostly in the out of plane direction on a sample surface or similarly utilize an in plane laser vibrometer to focus energy mostly in the in plane direction on a sample surface (with the direction of the in plane motion pertaining to the orientation of the in plane laser light).[5] With the ability to focus energy in 3 orthogonal directions (the out of plane direction, and two orthogonal in plane directions) at a single point on a sample surface, one can naturally utilize the TREND technique to inspect the nonlinear signatures of that point in three directions. Preliminary experiments to utilize 3D TREND (described above in this paragraph) to image the orientation of cracks and disbonding has been presented previously.[6] Here we present some further experiments, conducted on steel samples with cracks at known orientations, to demonstrate that the orientation of a crack may be imaged using 3D TREND. We utilize the scaling subtraction method (SSM)[7] to classify the nonlinear signature at each evaluation point.

EXPERIMENT SETUP

Figure 1(a) displays a photograph of the steel samples used in this study. One sample does not have a crack and is used as a control sample (on the left in the photo). The angles of the crack orientations are at 77°, 59°, 57°, and 29° relative to the sample's top surface (the x-y plane) for the samples from left to right as pictured (after the uncracked sample).

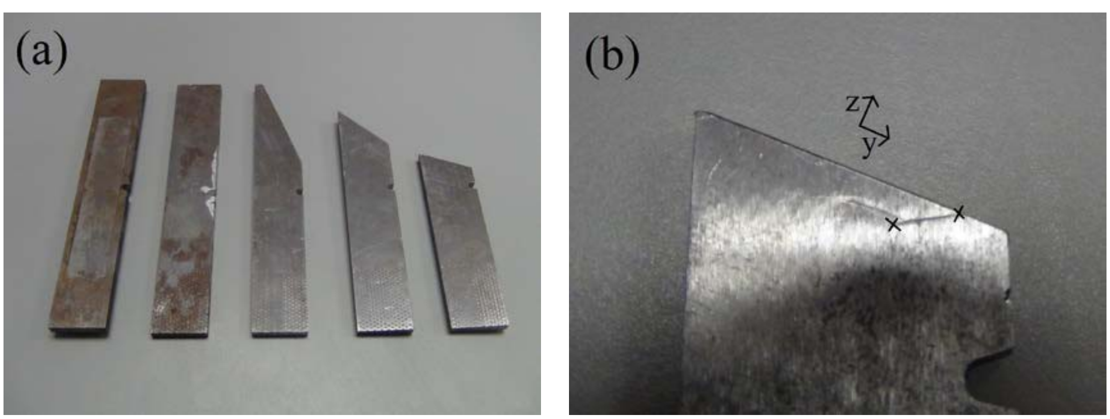

FIGURE 1. (a) Photograph of the 5 samples used in this study. (b) Photograph of one of the samples denoting the x, y, and z directions. The crack tips and ends are denoted in the photo.

Eight piezoelectric transducers were bonded (using epoxy) onto a vise that was then used to hold each sample under test. A TREND scan was then conducted with an out of plane laser vibrometer, and two scans with an in plane laser vibrometer at two orthogonal directions. We define the x, y, and z directions as shown in Fig. 1(b). Note the orientation of the crack on this 29° cracked sample as identified by the marks at the tip and the end of each sample.

A sampling frequency of 10 MHz and a time window of 32768 points (or 3.2768 ms in time) were used in the experiments. The source signal was a sinusoidal pulse of center frequency 75 kHz with a pulse length of 100 µs centered in the 32768 point window was used. For every recording made, 488 averages were done to improve the quality of each recording.

For each of the dimensions of the 3D TREND scan, the TREND procedure is repeated at 5 points spaced 1 mm apart in the x direction, and at 41 points spaced 0.25 mm apart in the y direction. The scanning is done with Cartesian positioning stages.

RESULTS

Scalerandi *et al*. proposed using a SSM residual metric to quantify the nonlinearity in experiments. In their paper they defined this metric, β, as the sum of the squared amplitudes over a selected period of time of the SSM residual signal. The SSM residual signal is found by making two measurements at different amplitudes, multiplying the lower amplitude signal by the constant representing the amplification difference between the two measurements, and then subtracting the high amplitude measurement from the scaled up lower amplitude measurement.

Here we wish to plot the instantaneous elastic kinetic energy for the *i*th focusing direction, E_{Ki}, that is related to β as follows

$$\beta_i = \frac{1}{T}\int_{t_1}^{t_2} u_i^{\,2} dt \tag{1}$$

$$E_{Ki} = \frac{1}{2}\rho_0 u_i^{\,2} = \frac{\rho_0}{2T}\int_{t_1}^{t_2} u_i^{\,2} dt = \frac{\rho_0}{2N}\sum_{n=1}^{N} u_i[n]^2 \tag{2}$$

where β_i is the SSM residual metric in *i*th direction of velocity focusing, T is the total time over which the integration takes place, t_1 is the start time for the integral, t_2 is the end time for the integral, u_i is the *i*th direction of velocity focusing, ρ_0 is the mass density (7800 kg/m^3 for steel), N is the total number of time samples summed for the integration, and n is the *n*th time sample. Figures 2 and 3 (different color scale normalizations) display the SSM results from the 3D TREND for the 29° cracked sample with the residuals from the x, y, and z directions plotted in (a), (b), and (c) respectively. It should be noted that the crack tip starts at (x = 0 mm, y = 7.5 mm) and ends at (x = 4 mm, y = 8.0 mm).

The x direction results show a gradual increase in E_{KX} from approximately y = 3.0 mm up to the crack tip where it peaks. This is likely the result of motion of the crack's knife edge moving significantly in the x direction relative to the other side of the crack, with a focus at the tip producing the largest motion.

The y direction results for E_{KY} should be expected to be fairly small since y motion should not cause the two crack surfaces to have significantly opposing motions. There is apparently some nonlinearity detected at points right at the crack tip, but still quite small in comparison to the energies in x and z.

The z direction results for E_{KZ} should be strongest at the crack tip as the two crack surfaces are forced to clap against one another. We see that this is the case in the results.

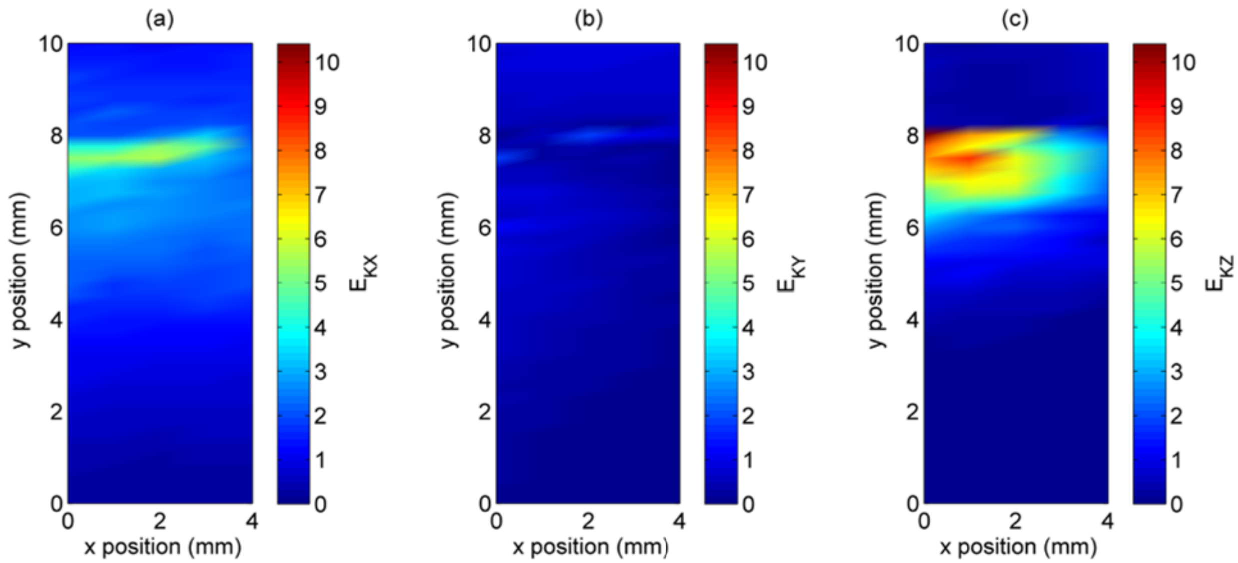

FIGURE 2. Spatial maps of the elastic kinetic energies of the SSM residual from the TREND results with the laser vibrometer setup in different directions for the 29° cracked sample: (a) x direction focusing using the in plane laser, (b) y direction focusing using the in plane laser, and (c) z direction focusing using the out of plane laser.

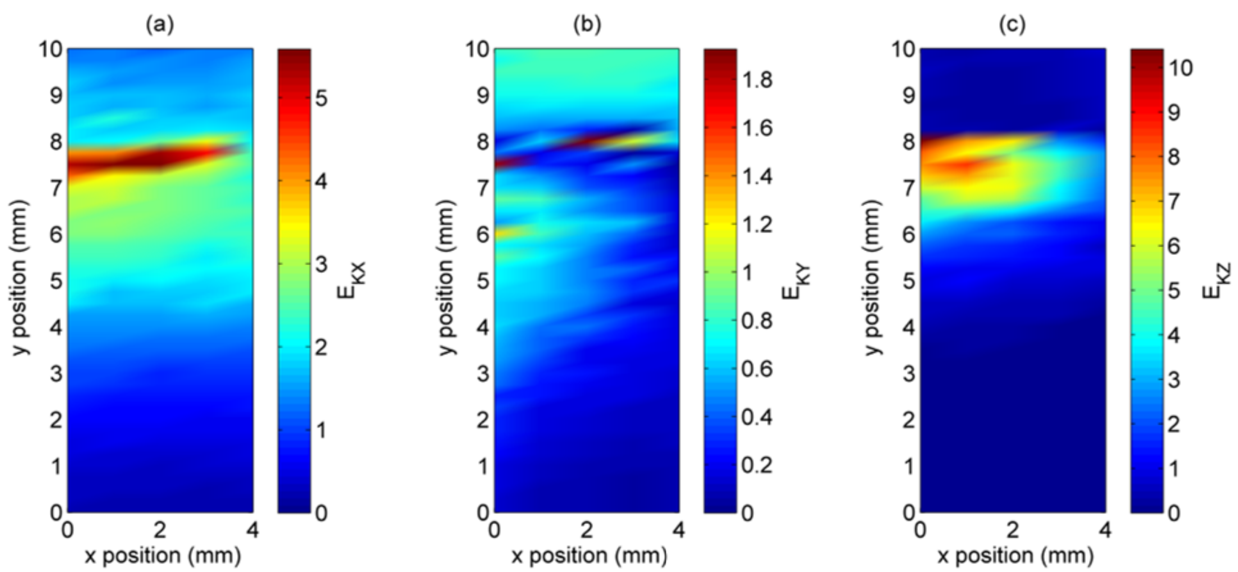

FIGURE 3. Spatial maps of the color-scale-normalized elastic kinetic energies of the SSM residual from the TREND results with the laser vibrometer setup in different directions for the 29° cracked sample: (a) x direction focusing using the in plane laser, (b) y direction focusing using the in plane laser, and (c) z direction focusing using the out of plane laser.

CONCLUSION

We have shown that 3D TREND, with the use of the SSM technique, can give physical insight into the orientation of a surface bearing crack. Further work will be conducted on the other samples to determine how the orientation of an unknown crack may be determined from similar experiments.

ACKNOWLEDGMENTS

This research was funded by the U.S. Dept. of Energy, Fuel Cycle R&D, Used Fuel Disposition (Storage) campaign.

REFERENCES

1. T. J. Ulrich, P. A. Johnson, and A. Sutin, “Imaging nonlinear scatterers applying the time reversal mirror,” J. Acoust. Soc. Am. **119**(3), 1514-1518 (2006).
2. M. Fink, Time reversed acoustics,” Phys. Today **56**, 143–147 (2000).
3. B. E. Anderson, M. Griffa, C. Larmat, T. J. Ulrich, and P. A. Johnson, “Time reversal,” Acoust. Today **4**(1), 5-16 (2008).
4. T. J. Ulrich, P. A. Johnson, and R. A. Guyer, “Interaction dynamics of elastic waves with a complex nonlinear scatterer through the use of a time reversal mirror,” Phys. Rev. Lett. **98**(10), 104301 (2007).
5. T. J. Ulrich, K. Van Den Abeele, P.-Y. Le Bas, M. Griffa, B. E. Anderson, and R. A. Guyer, “Three component time reversal: Focusing vector components using a scalar source,” J. Appl. Phys. **106**(11), 113504 (2009).
6. T. J. Ulrich, P.-Y. Le Bas, R. A. Guyer, B. E. Anderson, M. Griffa, and K. Van Den Abeele, “Three component time reversal imaging using nonlinear elasticity,” J. Acoust. Soc. Am. **125**(4), Abstract 2635 (2009).
7. M. Scalerandi, A. S. Gliozzi, C. L. E. Bruno, D. Masera, and P. Bocca, “A scaling method to enhance detection of a nonlinear elastic response,” Appl. Phys. Lett. **92**(10), 101912 (2008).