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► **To cite this version:**

B. van Damme, K. van den Abeele, Olivier Bou Matar. The vibration dipole : a time reversed acoustics scheme for the experimental localisation of surface breaking cracks. Applied Physics Letters, 2012, 100, pp.084103-1-3. 10.1063/1.3690043 . hal-00787355

HAL Id: hal-00787355

<https://hal.science/hal-00787355>

Submitted on 27 May 2022

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Cite as: Appl. Phys. Lett. **100**, 084103 (2012); <https://doi.org/10.1063/1.3690043>

Submitted: 13 December 2011 • Accepted: 08 February 2012 • Published Online: 23 February 2012

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The vibration dipole: A time reversed acoustics scheme for the experimental localisation of surface breaking cracks

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(Received 13 December 2011; accepted 8 February 2012; published online 23 February 2012)

A combination of time reversed acoustics and nonlinear elastic wave spectroscopy techniques is introduced to localize surface breaking defects in a non-destructive manner. Reciprocal time reversal is applied at two neighbouring positions in order to create a vibration dipole with high amplitudes. At surface breaking cracks, nonlinear elastic effects are triggered by the shear forces due to induced friction of the crack interfaces. By mapping the nonlinearity generated by the vibration dipole over the sample surface, the position of a surface breaking crack can be visualized. The technique is tested on an industrial steel sample containing a closed crack. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3690043>]

Time reversed acoustics (TRA) techniques provide the ability to focus ultrasonic waves in time and space.^{1–3} In classical TRA, a signal produced by an initial source is received, reversed in time, and re-emitted from the receiver position, causing a focused signal at the original source location. Using a laser vibrometer as a receiver and exploiting the reciprocity in space, high acoustic energies can be generated in any point on the surface of a material. This simple law of physics has been picked up by researchers dealing with ultrasonic non-destructive testing in order to locally activate the nonlinear stress-strain behaviour in zones that contain defects.

Over the last decade, innovative ultrasonic methods have been developed to probe the existence of damage (e.g., delaminations, micro-cracks, or weak adhesive bonds) by investigating various nonlinear signatures such as harmonic generation or pulse inversion (PI) asymmetry.^{4,5} Such approaches are termed nonlinear elastic wave spectroscopy (NEWS) techniques. Generally, the passage of a high amplitude wave suffices to trigger the nonlinear response.

Since high amplitude signals become more deformed than low amplitude waves, the fact that TRA can locally induce high amplitudes with good resolution has led to several concepts of merging the benefits of both TRA and NEWS in order to visualize the defects in solid samples.^{2,6,7} With nonlinear effects being defect selective and largely confined to the defect zone, a mapping of the nonlinearity value in a certain zone around the defect provides an indication of the defect position. The experimental sequence of a TRA procedure followed by a nonlinear filtering is referred to as TR-NEWS and has been applied in a variety of materials.^{2,3,8–10}

In this letter, a modification of the usual experimental TR-NEWS method is developed in order to efficiently excite and localize a surface breaking fatigue crack in an airplane

steering actuator bracket made of steel. Due to its size, geometry (Fig. 1), and low attenuation characteristics, a source signal applied at the surface of the sample will be reflected many times before being captured by a receiver. In this case, a good TRA focus can be achieved using only a few transducers, and even single channel TRA can be applied.¹¹ Two samples will be compared: an intact reference sample and a sample containing a fatigue crack. The fatigue crack is a surface breaking crack, meaning that the crack side interfaces are perpendicular to the sample's surface. It is closed at rest and measures about 9 mm long at the surface. The critical area of the bracket is indicated by the ellipse in the front view of the sample shown on Fig. 1.

In order to perform the TRA experiment, four magnetic source piezoelectric transducers (PZTs) were placed on the surface of the bracket as shown in Fig. 1. Although the quality of the TRA focus peak is good when using only one emitting transducer and one receiver, the use of four source

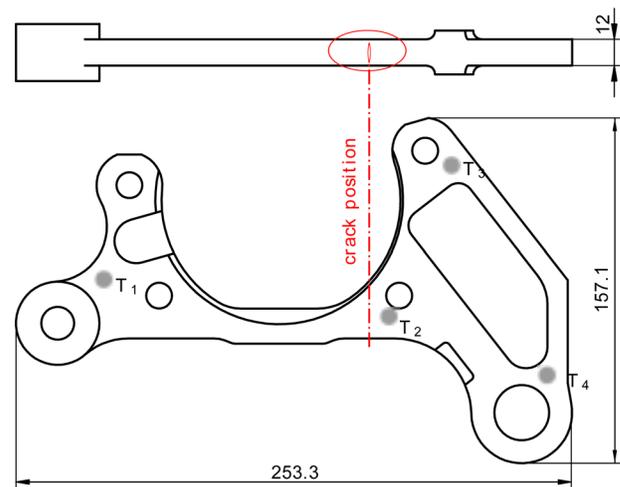


FIG. 1. (Color online) Front and top view of the sample, showing dimensions (in mm), critical zone, and crack position. The positions of the PZT transducers are labeled T₁–T₄.

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transducers allows us to increase the total acoustic energy in the sample, which helps for the activation of the nonlinearity. The number of transducers necessary for the experiment and their location on a certain sample surface is difficult to predict, and the influence of these parameters should be subject to further investigation.

To increase the quality of the TRA signal even more,^{8,12} a chirped excitation with a frequency ranging from 100 to 300 kHz was used as a source signal. The original source signals were injected sequentially, and the four response signals measured by a Polytec OFV-303 laser vibrometer (output scaling 5 V/mm/s) at a fixed point under investigation were stored individually. Only the out-of-plane velocities were measured and used in the TRA procedure. The signals are acquired by a PXI-5122 DAQ card with a sampling rate of 20 MHz. After acquisition and storage of the response signals, the four waveforms were inverted using the inverse filtering method,^{13,14} pulse compressed (i.e., intercorrelated with the time reversed input signal⁸), and rebroadcast simultaneously by the four corresponding PZTs. As a result of this multichannel reciprocal TRA mechanism, a high energy peak is produced at the considered location. The vibrometer is attached to a 2D stepper motor that allows to move the investigation point over the critical zone in steps as small as 0.1 mm. The entire setup is computer controlled by a LabVIEW program.

The motorized system can also be used to acquire the spatial distribution of the TRA focus at any point. An example of the TRA focus quality resulting from a maximum amplitude analysis is shown in Fig. 2. Typically, a more or less circular zone with a diameter at half maximum power of about 3.5 mm is excited.

Crack surfaces that are rubbing each other undergo frictional forces which are known to produce nonlinear effects.^{15–17} In order to activate this frictional behaviour, the traditional TR-NEWS technique should be modified to induce two high amplitude pulses with opposite directions

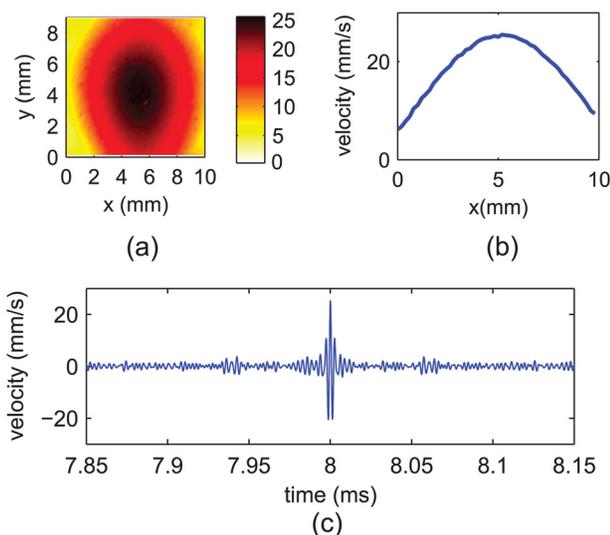


FIG. 2. (Color online) Time reversal experiment using a chirped source signal, pulse compression, and inverse filtering on the steering actuator bracket. (a) shows the maximum amplitude of the TRA signal around the focus in 2D. (b) is for a horizontal line through the focus centre. (c) shows a zoom of the time signal at focal time in the focus centre.

on both sides of the crack, a so called vibration dipole. Since time reversal is a linear operation, this dipole effect can be achieved by sequentially measuring a response signal produced by a single source on a position left and on a position right of a fixed central location. After the time reversing operation, it suffices to subtract both resulting signals and to rebroadcast the difference signal from the original source position. Instead of resulting in one single TRA peak, two peaks with opposite phases will now be created at the corresponding positions of both received signals.

The dipole vibration TRA result for a chirped signal, after applying pulse compression and inverse filtering, measured for a scan over a zone covering two original receiving points separated by a distance 6 mm is given in Fig. 3. The line scan shown in Fig. 3(b) clearly demonstrates that the motion is opposite on the left and the right hand side of the central location.

Having checked the particular nature of the vibration dipole response in this modified TRA experiment, the concept can now be used to trigger the friction characteristics of a surface breaking crack if both peaks are at a different side of the crack. In order to quantify the level of friction (indirectly), a measure of the on-crack nonlinear response was defined by means of a PI filter.^{2,18} For this, the phase inverted version of the TRA signal (as defined above) was rebroadcast as well, now resulting in a negative peak at the left and a positive peak at the right side of the point under consideration. Following the zero-phase and phase-inverted dipole TRA operations, the sum signal of the two responses at the centre of the dipole was stored and analysed. If there is no nonlinearity, the sum signal should approximate a flat line. In case of nonlinearity (induced by a crack), the resulting signal should be non-zero at the focal time. We finally defined the nonlinear signature derived from this operation as the signal to noise ratio (SNR) of the focus peak of this PI-filtered signal, i.e., the square root of the ratio between the total energy in the focus peak and the mean energy of the rest of the signal. The time length of the focus peak is in the order of 10 μ s.

In order to optimize the shearing activity, we first investigated the influence of the dipole distance on the on-crack nonlinear response. To avoid imprecisions due to random measuring errors or small positioning errors, 9 signals were received on a small 3×3 grid with a 0.1 mm spacing at the expected centre of the crack. The mean values of the 9

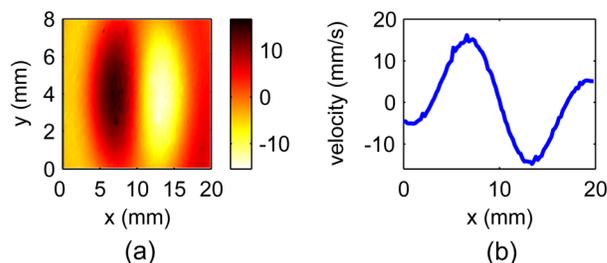


FIG. 3. (Color online) Illustration of the dipole vibration TRA showing the 2D distribution of the measured amplitudes around the double peak focus zone (plot (a)). The amplitudes vary from -15 mm/s to 15 mm/s. The line plot (b) corresponds to the amplitudes on a horizontal line connecting the two focal points within the scanned zone (a).

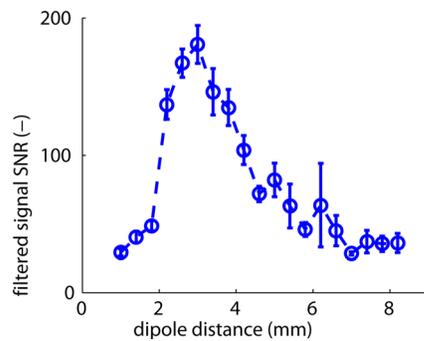


FIG. 4. (Color online) Investigation of the on-crack measured nonlinear contribution using a vibration dipole TRA experiment showing the SNR of the PI-filtered signals as a function the dipole distance.

calculated SNR values of the nonlinear response are shown in Fig. 4 for dipole distances between 1 and 9 mm. For very small distances, the poor response can be attributed to the fact that the two opposite phase pulses generated by the TRA operation produce a significant cancellation of the amplitudes near the centre. An optimum is reached for a dipole distance of 3 mm, followed by a contrast decrease for larger distances. The value of 3 mm agrees well with the theoretical distance for a maximal velocity gradient caused by two adjacent phase inverted Gaussian peaks with 2.5 mm diameter at half power. At this distance, the large velocity gradient causes the largest localised shear stresses.

In a next step, this optimal peak distance of 3 mm was used to visualize the crack location by generating vibration dipoles with centres covering a zone around the crack position. When both peaks are at the same side of the crack, both the crack sides remain at the same relative positions. If one peak is located left and the other peak right of the crack, they will force the two crack interfaces to slide, thus generating a nonlinear wave distortion.

The actual vibration dipole TRA experiment was carried out using a chirped source signal (100-300 kHz), followed by pulse compression and inverse filtering. A $6\text{ mm} \times 8\text{ mm}$ zone around the crack was scanned with a 0.2 mm step using a laser vibrometer as receiver. The local nonlinear behavior at the centre of the dipole was analysed using the PI technique as a nonlinearity filter.

The final results of the dipole TRA experiment on the fatigued and the intact brackets for a dipole separation distance of 3 mm are summarized in Fig. 5. Part (a) shows the SNR of the PI-filtered signals on the damaged bracket, revealing a distinct zone of high nonlinear response. The result for the undamaged bracket is presented in Fig. 5(b)

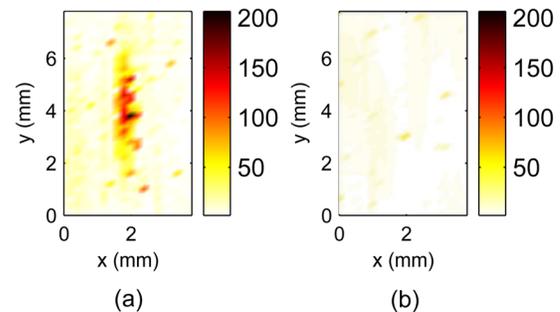


FIG. 5. (Color online) Nonlinear signatures (SNR after pulse inversion filtering) obtained with the vibration dipole TRA experiment for the two samples. The damaged bracket (a) shows a clear nonlinear response. The undamaged bracket (b) shows no localized nonlinearity.

showing no evidence of a localised nonlinear response at the critical zone.

The TR-NEWS variant called the vibration dipole that was introduced in this letter proved to be efficient in detecting a surface breaking crack in an industrial steel sample. Due to the particular nature of the induced motion, the method also delivers experimental evidence of nonlinear wave distortion generated by friction between the crack's faces.

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