NONLINEAR ELASTIC WAVE NDE II. NONLINEAR WAVE MODULATION SPECTROSCOPY AND NONLINEAR TIME REVERSED ACOUSTICS[□]

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ABASTRACT. This paper presents the second part of the review of **Nonlinear Elastic Wave Spectroscopy (NEWS)** in NDE, and describe two different methods of nonlinear NDE that provide not only damage detection but location as well. **Nonlinear Wave Modulation Spectroscopy** is based on the application of an ultrasonic probe signal modulated by a low frequency vibration. Damage location can be obtained by application of Impulse Modulation Techniques that exploit the modulation of a short pulse reflected from a damage feature (e.g. crack) by low frequency vibration. **Nonlinear Time Reversed Acoustic** methods provide the means to focus acoustic energy to any point in a solid. In combination, we are applying the focusing properties of TRA and the nonlinear properties of cracks to locate them.

INTRODUCTION

This paper continues the review of Nonlinear Acoustic NDE methods started in the previous paper [1]. Here we describe methods that provide not only the means for damage detection but location as well. Nonlinear Wave Modulation Spectroscopy (NWMS) is based on the application of an ultrasonic probe signal modulated by a low frequency vibration. The nonlinearity due to the presence of damage manifests itself as side-band (intermodulation) components in the spectrum of the received signal. Damage location can be obtained by application of a variation of the technique that exploits the modulation of a short pulse reflected from a damage feature (e.g. crack) by low frequency vibration [2].

Time Reverse Acoustic (TRA) methods are perfect tools for focusing of acoustic energy to any point within a sample. The nonlinear response in the focused signal can be used for damage detection and localization.

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NONLINEAR WAVE MODULATION SPECTROSCOPY

One of the simplest ways to evaluate nonlinear acoustic properties of a material is to measure the modulation of an ultrasonic wave by low-frequency vibration [1-6]. This method is known as nonlinear wave modulation spectroscopy (NWMS). The physical nature of this modulation can be explained simplistically as follows. Consider the sample shown in Figure 1 with a single crack shown as a slit. An applied low-frequency vibration signal changes the width of the slit depending on the phase of the vibration. As an example let us consider the case where the sample is under sufficient vibration amplitude that the compression phase completely closes the crack (Figure 1a), whereas the subsequent dilation opens the crack (Figure 1b). A high-frequency signal is simultaneously applied to the crack. During the dilation phase of the low-frequency cycle, the high-frequency signal is partially decoupled by the open crack. This reduces the amplitude of the high-frequency signal passing through the crack. In the other half of the low-frequency cycle, the closed crack does not interrupt the ultrasonic signal and the amplitude of the transmitted signal amplitude increases. This results in an amplitude modulation of the ultrasonic signal as shown in Figure 2. Fourier transformation of this signal reveals sideband frequencies that are the sum and difference of the frequencies of the ultrasonic probe and vibration signals. These new frequency components indicate that a flaw or crack is present. This simple model provides physical intuition but cannot be used for quantitative assessment. More realistic crack models describing cracks as contacting rough surfaces are presented in [7-9].

The following experiment demonstrates an application of a similar technique to test an alternator housing produced by Ford Motor Company. The experimental setup is shown in Figure 3. Soft foam supported the samples. Ultrasonic transducers were glued to the sides of each sample. Low-frequency, broadband vibration was generated with an

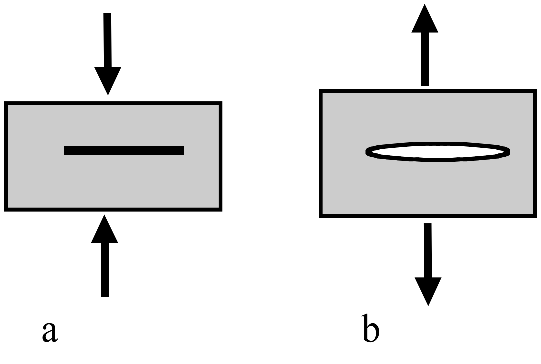

Figure 1. Sample with flaw:
a - closed by vibration compression, b - open under dilation.

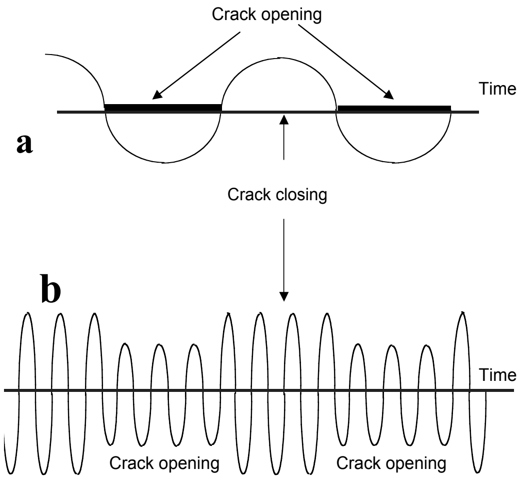

Figure 2. Amplitude modulation of probe signal: (a) vibration, (b) ultrasonic signal.

instrumental hammer, which produced repeatable impacts with controlled amplitude (500 N). The hammer was equipped with a sensor used for synchronization with the data acquisition system. The spectrum of the signal for an intact part is compared with that from a part with a tiny crack in Figure 4. It can be seen that modulation (high magnitude of the sideband components) is present for the damaged part. The intact sample has no side components.

These and other experiments demonstrate a dramatic damage-induced effect on the cross-modulation of low-frequency and high-frequency acoustical waves in the material. Figure 5 shows same parts that were checked by application of NWMS, and some results of testing are presented in references [4-6].

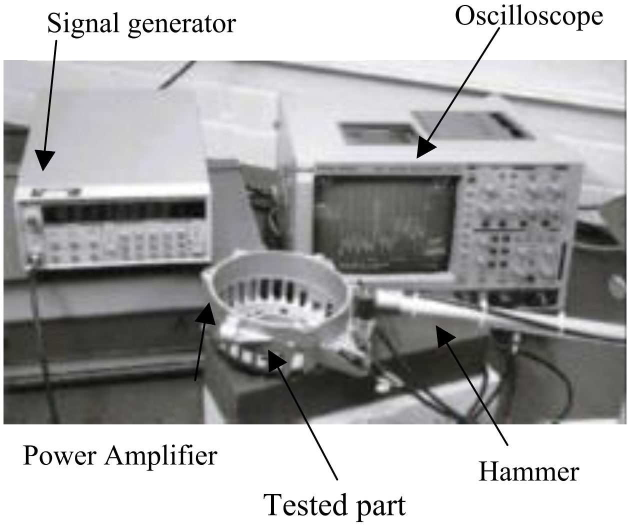

Figure 3. Experimental setup for alternator housing test

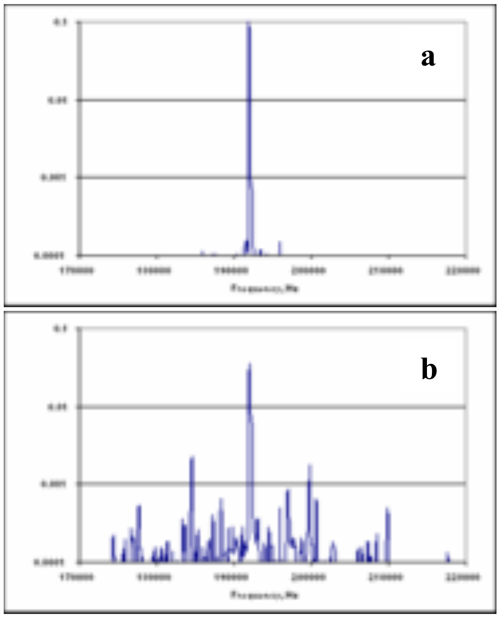

Figure. 4. Spectra of the received signal for a) the intact sample, and b) the sample with a tiny crack.

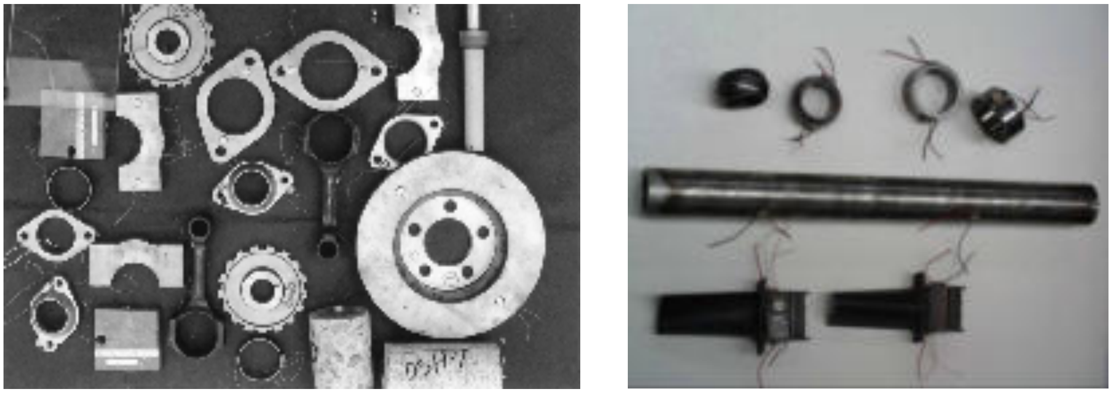

Figure. 5. A number of tested parts.

Various tested parts and materials include:

1. Stress-corrosion cracks in steel pipes (Gas Research Institute, Chicago, IL).
2. Bonding quality assessment in titanium and thermoplastic plates used for airspace applications (Boeing).
3. Cracks in aircraft steel fuse pins (Boeing).
4. Cracks in combustion engine parts (Ford).
5. Cracks and corrosion in reinforced concrete (DARPA).
6. Damage in Asphalt (National Highway Administration)
7. Cracks in different automotive parts (General Motors).
8. Accumulated damage from cycled loaded steel parts (Purdue University, Calumet).
9. Cracks in glass (Los Alamos National Laboratory; University of Le Mans, France).
10. Cracks in polycarbonate used for aircraft fuselage (University of Purdue, Calumet).
11. Cracks in titanium alloys used in aircraft engines (Honeywell, AR)
12. Titanium rotor blades (Volvo, Sweden).
13. Damage in bearings caps and rings of different forms from sintered metal (SKF, Sweden).

Nonlinear Modulation Method of Crack Location

The NWMS technique described above provides high sensitivity for "pass –fail" tests but cannot be used to locate a crack. One method of crack location can be obtained by a pulse modulation method. The concept is shown in figure 6.

The acoustical transducer in conventional pulse-echo techniques produces an ultrasound impulse propagating in the specimen. This impulse is reflected from different kinds of inhomogeneities. For example, the reflected signals from a hole and a crack are presented in Figure 6 (left panel). Reflected signals form the crack and the hole come at different times but there is no way to distinguish what signal is reflected from the crack and what signal from the hole. These signals can be distinguished if nonlinear means are employed, in this case applying the pulse-echo technique in the presence of low-frequency vibration. The vibration amplitude and phase of the ultrasound signal reflected from crack will be modulated, while the signal reflected from linear defect (the hole) has no modulation.

The upper part of the right panel of Figure 6 presents the harmonic vibration with low frequency. Signals reflected from the hole are marked by letter **H** and signal reflected from the cracks are marked by **C**.

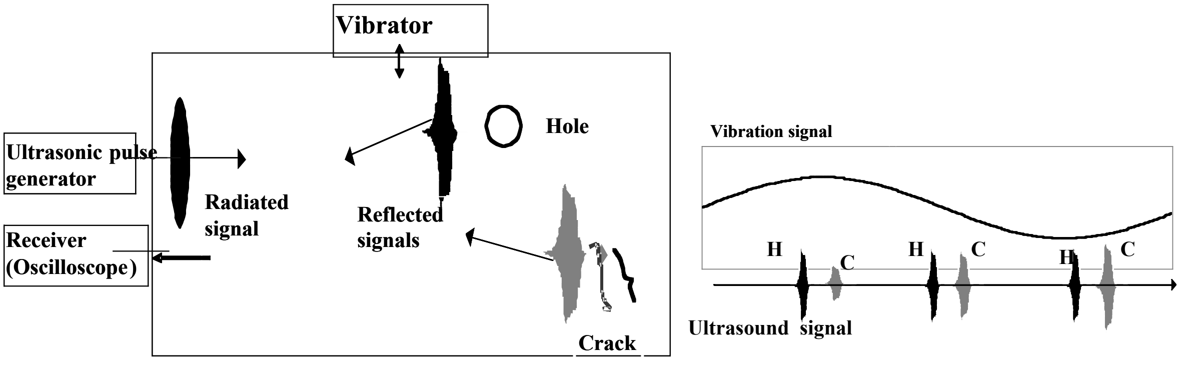

Figure 6. Concept of a pulse modulation method.

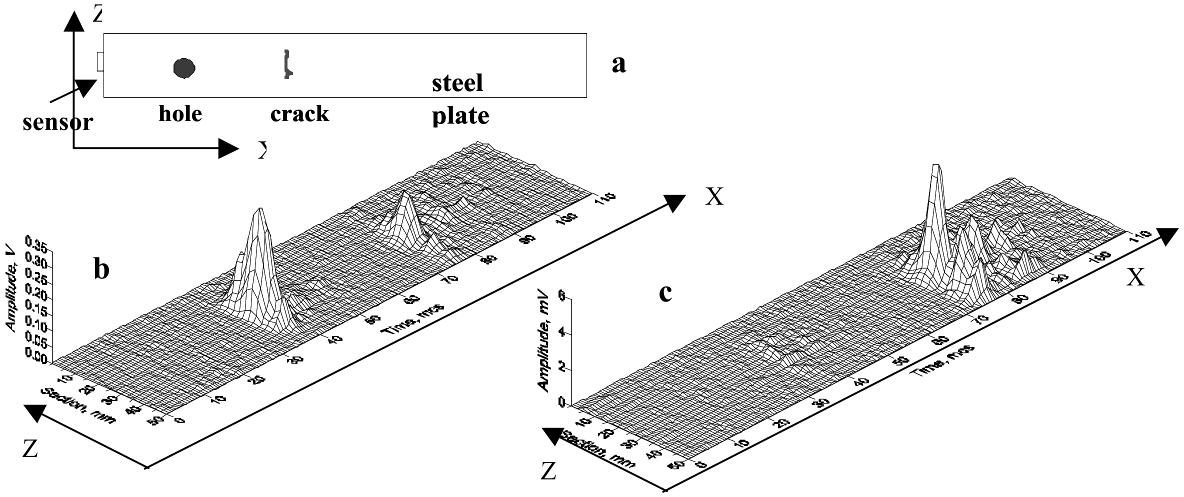

Figure 7. Results of pulse modulation method test; a) schema of plate, b) spatial distribution of the linear scattered signal, d) spatial distribution of the modulation index (nonlinear scattering).

The lower part of the right panel shows signals reflected from the defects at different times. The first pair is reflected at the moment when the applied vibration stress reaches the maximum. At this time the crack is compressed and the signal reflected from the crack has minimal amplitude. The second pair of impulses is shown at time when the vibration stress is small and there is no change in the reflected impulse. The third pair shows the extension phase of the vibration at that moment the crack is maximally opened and the reflection signal is higher than in previous phases. The modulation of this signal allows one to distinguish crack-like defects from other inhomogeneities.

Experimental verification of the pulse modulation method are presented in [10]. In this experiment the linear and nonlinear scattering from the hole and the crack created by cyclic loading was measured in steel plate having dimension 50 x 305 x 6 mm. Ultrasonic pulses with frequency 3MHz was used for location and vibration with frequency 10 Hz was produced by a shaker. Panel **a** of Figure 7 shows the geometry of the experiment. 3-D pictures in Figure 7 present the distribution of the amplitude of the scattered signal in the tested plate (Figure 7**b**) and level of modulation in the scattered signal (nonlinear scattering Figure 7**d**). Axis Z is the transverse coordinate of the plate where the sensor was placed. The distance between the sensor and the point of reflection is measured along the X-axis. This coordinate is connected with the time of the reflected signal.

It is clearly seen that the linear technique gives very similar signals from the crack and the hole whereas the nonlinear processing provides a clear difference between the crack and defects that do not produce nonlinear properties (like holes).

NONLINEAR TIME REVERSED ACOUSTIC NDE

Time Reverse Acoustical (TRA) methods provide the means to focus acoustic energy [11-12]. The focused TRA signal can have high amplitude making it a perfect tool for inducing nonlinear effects. We are exploiting the focusing properties of TRA and the elastic nonlinear properties of cracks together to develop methods for crack and damage location.

Much of the seminal research in TRA has been carried out by the group located at the University of Paris VII (Laboratoire Ondes et Acoustique, ESPCI) [11-15], who have demonstrated the ability and robustness of TRA (using Time Reversal Mirrors) to provide spatial and temporal focusing of an ultrasonic wave. A significance aspect of TRA is that it provides one the ability to focus an ultrasonic wave, regardless of the position of the initial source and regardless of the heterogeneity of the medium in which the wave propagates. TRA systems have a range of applications, including destruction of tumors and kidney stones and long-distance communication in the ocean. The NDE applications of TRA to date include detection of small, low-contrast defects within titanium alloys [13,14] and detection of cracks in a thin air-filled hollow cylinder [15]. Recent modeling of TRA in solids was conducted in [16]. A review of TRA applications to NDE is given in [13].

We conducted a demonstration experiment in a glass parallelepiped with dimensions of 101 x 89 x 89 mm^3 [17]. A piezoceramic disk, 50 mm in diameter and 2.8 mm thick, was glued using epoxy near the corner of one side of the glass parallelepiped as shown in Figure 8. A laser vibrometer (Polytech) was used as detector. The time reversal experiment was carried out using the following steps:

Step 1. A short Gaussian shaped electric pulse with carrier frequency of 260 kHz was applied to the first transmitter (Fig. 9a). The selected frequency was near the resonance frequency of the transducer.

Step 2. The signal that arrived at the opposite side of the sample (not far from the sample center) was measured by a laser vibrometer (Fig.9b). The detected signal was then band-pass filtered (210-310kHz) to eliminate harmonics produced by equipment nonlinearity.

Step 3. The recorded signal was time reversed as shown in Fig.9c (normalized to 1V p-p). The signal was stored in the operative memory of the TRA system.

Step 4. The TR signal was re-radiated.

Step 5. The TRA focused signal was recorded by the laser vibrometer and analyzed. A typical TRA focused signal is shown in Fig. 9d.

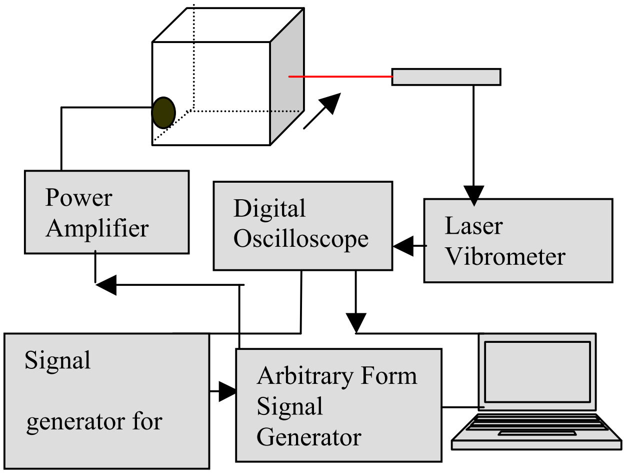

Figure 8. The experimental setup for TRA focusing in a glass parallelepiped sample.

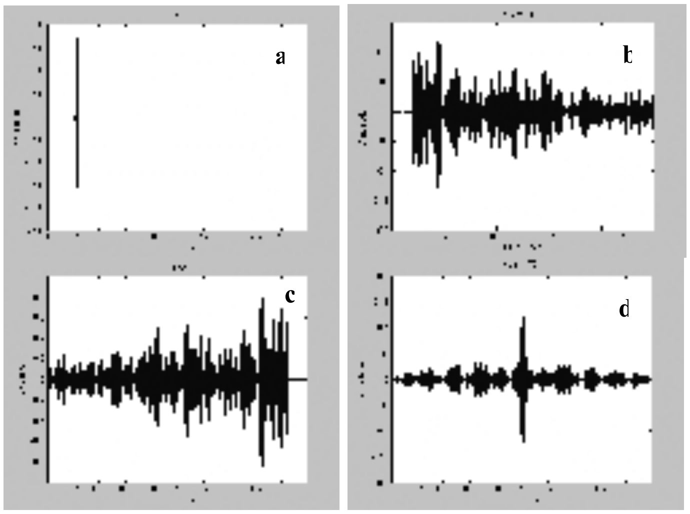

Figure 9. TRA focusing in the glass: a) initial radiated in Step 1 r.f. signal, b) direct recorded signal of Step 2, c) radiated TR signal, d) detected focused TR signal.

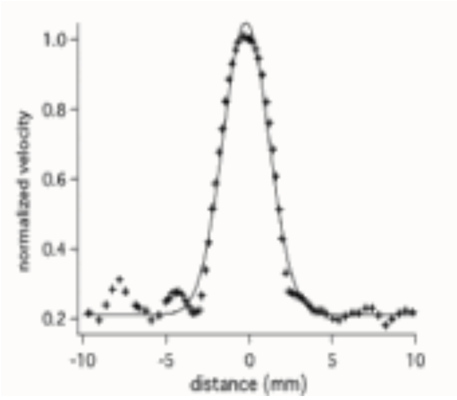

Figure. 10. The spatial distribution of the TRA focused signal amplitude

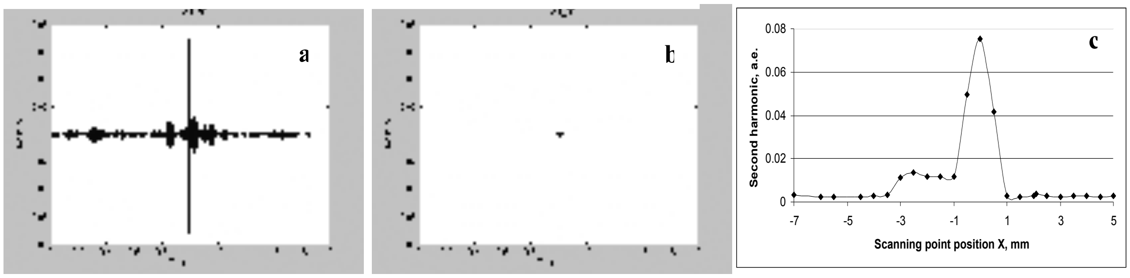

Figure 11. The TRA focused signal filtered around second harmonics (520 kHz): a) signal on the surface above the crack, b) signal on an intact surface, c) spatial distribution of the second harmonic amplitude along the sample surface.

The spatial distribution of the TRA focused signal amplitude for the frequency 260 kHz band is presented in Fig. 10. Amplitudes are the measured peak amplitudes of the TR signal at each position, normalized to the maximum measured amplitude.

For observation of nonlinear effects, narrow band filtering was used with a central frequency of 520 kHz that detects the second harmonic of the TRA focused signal. Figure 11 shows the detected TRA signals filtered at 520 kHz for the laser detector recording from the surface above the crack, and from the intact surface. It can be seen that that the amplitude of the second harmonic of the signal detected above the crack is much higher than the amplitude of the harmonic from the intact surface signal.

The high elastic nonlinearity due to the presence of a crack can be used for crack location. By scanning the surface using the laser vibrometer in tandem with TR focusing at each scan point, then analyzing for nonlinear response at that point, one can determine if cracks exist in the scanned area. The feasibility of this technique, called Nonlinear Time Reverse Acoustical Imaging NTRAI, was evaluated in an experiment where the TRA focusing was conducted along a single line scan in a glass sample with and without damage present. Figure 11c presents the dependence of the second harmonic amplitude on the X coordinate along the glass sample surface. A high level of the second harmonic was observed above the crack while the second harmonic was negligible when scanning took place away from the crack. As it is seen in Figure 11c, NTRA shows the small crack (diameter about 2 mm) profile. This experiment demonstrates the feasibility of the application of Nonlinear TRA for crack imaging.

In summary, in this paper we have described Nonlinear Wave Modulation Spectroscopy (NWMS) for damage diagnostics and imaging, and Nonlinear Time Reverse Acoustics Imaging (NTRAI) for damage location. In the previous paper [18] in this volume, we described two other methods that can be applied to determine whether or not damage is present: Nonlinear Resonant Ultrasound Spectroscopy (NRUS) and Slow Dynamics Diagnostics (SDD). These techniques promise powerful new manners by which to diagnose the presence of damage and determine its location.

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