LA-UR-04-6426

Approved for public release; distribution is unlimited.

Title: NONLINEAR ELASTIC WAVE NDE I. NONLINEAR RESONANT ULTRASOUND SPECTROSCOPY (NRUS) AND SLOW DYNAMICS DIAGNOSTICS (SDD)

Author(s): Paul A. Johnson, [redacted], EES-11

Alexander Sutin, V#832245, Davidson Laboratory, Stevens Inst. of Tech.

Submitted to: QNDE Proceedings, Golden, CO

Los Alamos
NATIONAL LABORATORY

NONLINEAR ELASTIC WAVE NDE I. NONLINEAR RESONANT ULTRASOUND SPECTROSCOPY (NRUS) AND SLOW DYNAMICS DIAGNOSTICS (SDD)

P. A. Johnson[1] and A. Sutin[2]

[1]Geophysics Group, Los Alamos National Laboratory of the University of California, Los Alamos, NM 87545
[2]Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ 07030

ABSTRACT. The nonlinear elastic response of materials (e.g., wave mixing, harmonic generation) is much more sensitive to the presence of damage than the linear response (e.g., wavespeed, dissipation). An overview of the four primary **Nonlinear Elastic Wave Spectroscopy (NEWS)** methods used in nonlinear damage detection are presented in this and the following paper. Those presented in this paper are **Nonlinear Resonant Ultrasound Spectroscopy (NRUS)**, based on measurement of the nonlinear response of one or more resonant modes in a test sample, and **Slow Dynamics Diagnostics (SDD)**, manifest by an alteration in the material dissipation and elastic modulus after application of relatively high-amplitude wave that slowly recovers in time.

INTRODUCTION

Over the last two decades, studies of nonlinear acoustic effects in samples of rock and engineering materials have markedly increased [1-3]. The studies have focused on basic research of elastic nonlinear material response as well as development of damage diagnostics. Numerous nonlinear quasistatic and dynamic observations demonstrate that the nonlinear elastic response of the materials may radically increase in the presence of mechanically "soft" inclusions in a hard matrix (e.g., a crack in a solid) [1]. The defects *must* be mechanically soft to induce a nonlinear response. For instance, a crack will induce elastic nonlinear response, but a void will not. Thus these methods provide a means to distinguish between cracks and other damage in the presence of voids or other features that may be unrelated to damage. Further, these studies show that the macroscopic nonlinear response in a material is dependent on the integral quantity of defects that exist within the material [1-3], meaning progressive damage can be monitored in a very sensitive manner.

Historically, the first applications of the nonlinear response for material characterization employed measurements of the second harmonic generated by the nonlinear distortion of a sinusoidal acoustic wave propagating in a medium with damage. The first test of this method was made as early as in 1979 in wave propagation experiments [4]. The second harmonic method has been highly developed and is now routinely used in numerous applications [5-7], including medicine [e.g., 8].

Over the last 15 years it has become clear that analysis of harmonic generation is not the only, and not always the best, manner to extract the nonlinear response. Other nonlinear techniques have been developed including those from the pioneering experiments applying cross-modulation (frequency mixing) of low and high-frequency sound waves conducted at the Institute of Applied Physics, Nizhniy Novgorod, Russia [9] and studies of the amplitude dependence in resonance studies conducted at Los Alamos National Laboratory and the Catholic University, Belgium [10-11]. Resonance methods require much less acoustic power than the travelling-wave methods due to the self-amplification that occurs during wave resonance.

In all these studies it was found that the nonlinear methods turn out to be more sensitive to damage than any known method based on the measurements of linear parameters such as wave speed and attenuation. It was also confirmed that the macroscopic nonlinear response of a material is largely determined by its microstructure, which is understood as structural defects with the scales small as compared to the sample size and the acoustic wavelength.

In summary, the established nonlinear wave methods are termed Nonlinear Elastic Wave Spectroscopy [3]. Sub-categories are based on modulation of two or more waves [Nonlinear Wave Modulation Spectroscopy (NWMS)] [1] and material resonance [Nonlinear Resonant Wave Spectroscopy (NRUS)] [1]. New methods have recently appeared as well. One is based on a strain memory effect known as *slow dynamics* [12,13] and is termed Slow Dynamics Diagnostics (SDD). The second is based on Time Reverse Acoustics [14] and is termed Nonlinear Time Reverse Acoustics (NTRA).

In this paper and the following, companion paper [14], we provide an overview of the above, four primary NEWS methods of Nonlinear NDE. This paper describes Nonlinear Resonant Wave Spectroscopy (NRUS) and Slow Dynamics Diagnostics (SDD). The companion paper [15] describes Nonlinear Wave Modulation Spectroscopy (NWMS) and Nonlinear Time Reverse Acoustics (NTRA).

THEORY

Nonclassical Nonlinear Fast and Slow Dynamics

Fundamentally, elastic nonlinearity implies that the stress-strain relation (also known as the equation of state, EOS), is nonlinear. Figure (1a) shows a linear (Hookian), and progressively more *classical* nonlinear EOS. For such a relation, the one dimensional modulus can be described by

$$K(\varepsilon) = K_o(1 - \beta\varepsilon + \alpha\varepsilon^2 + ...), \qquad (1)$$

where K_o is the linear modulus, and β and δ are the first and second order classical nonlinear parameters. At low dynamic wave amplitudes, solids with cracks appear to behave in a manner according to Eq. (1). As wave amplitudes increase into the range of 10^{-6} strain amplitude, the material response begins to exhibit hysteretic behavior where,

$$K(\varepsilon,\dot{\varepsilon}) = K_o(1 - \alpha(\Delta\varepsilon + \varepsilon(t)sign(\dot{\varepsilon})) + ...), \qquad (2)$$

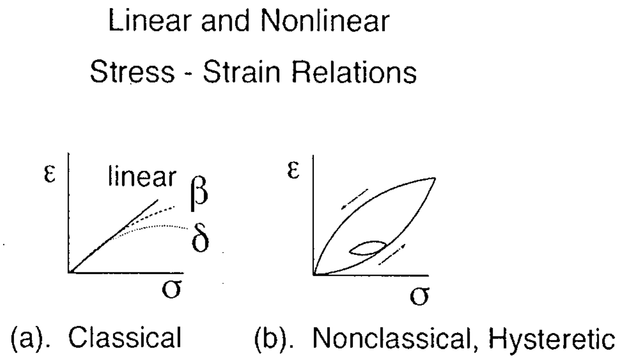

FIGURE 1. Linear and classical (a), and nonclasssical, hysteretic (b) stress-strain relations.

where K_o is the linear modulus, $\Delta\varepsilon$ is the peak strain amplitude over a wave period, $\dot{\varepsilon} = \partial\varepsilon/\partial t$ is the strain rate, and ($sign\ (\dot{\varepsilon})\ =\ 1$ for $\varepsilon \rangle 0$) and ($sign\ (\dot{\varepsilon})\ = 1$ for $\varepsilon \langle 0$)) [16]. There are other characteristics or the hysteretic EOS that are described elsewhere [e.g., 1,2].

The nonlinear coefficient α describes the quantity of hysteresis in the EOS. As α increases, so does the hysteresis in the EOS. Equation (2) indicates that as the wave strain amplitude increases, the modulus changes as well, this time however in a discontinuous manner (a butterfly-type behavior) in contrast to the classical behavior described in Eq. (1). The average modulus is found to always decrease with strain amplitude in solids with defects (α, is always positive). As a result we have, in the case of hysteresis being the dominant cause of nonlinearity, that the features in the material contributing to the nonlinearity make a contribution to the motion of the displacement field that depends on the actual strain value, the strain derivatives and the strain amplitude in a typically nonanalytic manner. For more regarding the development of the wave equation see [2].

In addition to hysteresis, cracked material exhibits the phenomenon of *slow dynamics*, meaning that, once disturbed by a wave in the strain amplitude regime corresponding to hysteresis, the material takes time to return to the rest state modulus K_o relaxing as the logarithm of time [see, e.g., 12]. Slow dynamics can be a powerful indicator of nonlinearity and of therefore damage.

NONLINEAR RESONANT ULTRASOUND SPECTROSCOPY

Nonlinear Resonant Ultrasound Spectroscopy (NRUS) is based on the measurement of resonance frequency shift and material damping as a function of resonance peak amplitude for one or several resonance peaks [3,10,11]. This method is an extension of linear Resonant Ultrasound Spectroscopy (RUS) that is widely used in industrial NDE [17]. In this type of measurement, the change in resonance frequency of a mode with drive amplitude is a measure of the wavespeed and modulus change. For instance, in a simple geometry such as a cylindrical bar driven at the fundamental mode, the wavespeed c is,

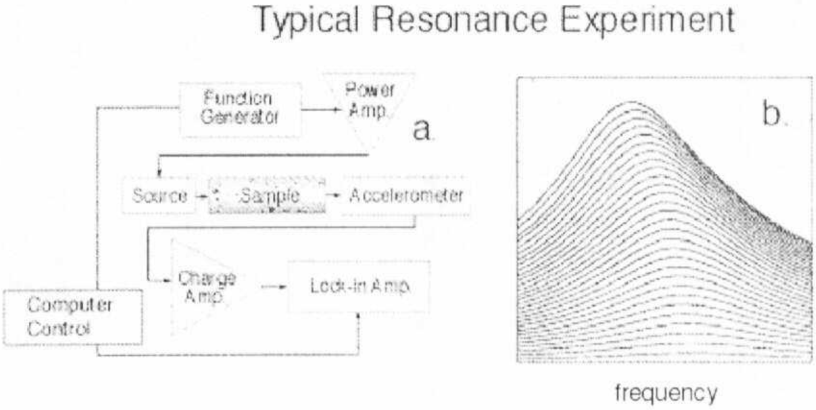

FIGURE 2. (a) Typical NRUS configuration and (b) resonance curves obtained from a damaged solid. The source drives at a sequence of frequencies stepping from below to above a resonance modal peak. A lock-in amplifier is used to extract the time average amplitude of the detected signal. The signal response is shown in (b). The amplitude is increased and the procedure is repeated progressively. In a damaged material, the peak shifts downward with drive amplitude as shown in (b).

$$c = f\lambda = 2fL = \sqrt{\frac{K}{\rho}} \tag{3}$$

where f is resonance frequency of the fundamental mode, λ is the wavelength, L is the bar length, K is modulus and ρ is density. The equation becomes correspondingly more elaborate for more complicated sample geometries.

A typical resonance experimental configuration is shown in Figure 2. In the following we show application of NRUS to a steel specimen under cyclic loading conditions. Seven standard steel specimens (Figure 3) were tested under programmed cyclic loading on a fatigue-testing machine, each accumulating progressively more damage. Both linear and nonlinear acoustic techniques were used to assess damage accumulation.

Figure 4 shows the NRUS result from two of the steel samples, one virtually "intact" measured in the undamaged state (left), and one measured at 90% of failure (right).

Figure 5 shows the NRUS results for all of the samples tested. The data in this plot are the resonance peak amplitudes plotted against their respective particle velocities. The data show that, qualitatively, the change in resonance frequency with amplitude increases dramatically with accumulated damage.

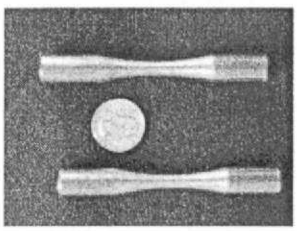

FIGURE 3. Steel specimens used for cyclic load measurements. Quarter dollar used for scale.

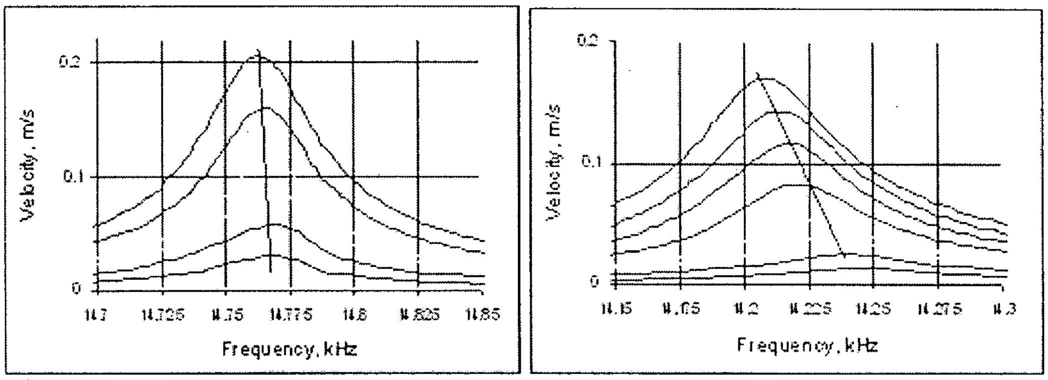

FIGURE 4. NRUS measurements on steel samples shown in Figure 3. (a) shows results for an intact, undamaged sample. Note that it exhibits a small amount of peak shift, meaning it is slightly elastically nonlinear in the intact state. This is due to high dislocation density in the sample. (b) shows sample measurements taken from a sample that was fatigued to within 90% of failure. It is significantly more nonlinear in that the peak shift is pronounced and the material dissipation characteristics are increased.

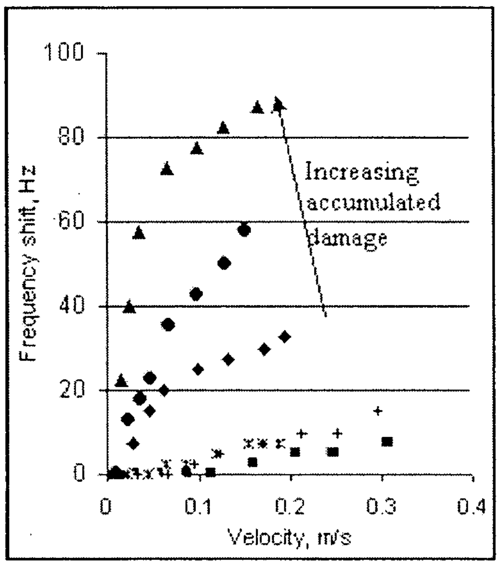

FIGURE 5. NRUS measurements from all steel samples. Note the huge shift in resonance frequency for the sample measured near failure. (the frequency axis is the change in resonance frequency from the intact state). The linear wavespeed and inverse dissipation (Q) changes were immeasurable until approximately 80% of failure.

SLOW DYNAMIC DAMAGE DIAGNOSTICS

To reiterate, when a damaged material is strained by an oscillatory-wave or impulsive source at small amplitudes (10^{-6} - 10^{-7}) the elastic wave present in the material distorts, manifest by resonance modal changes, wave speed decrease and the creation of harmonics and wave modulation. If the strain amplitude is sufficiently strong ($>\sim 10^{-6}$) the material does not immediately recover to its original state. Instead, it recovers to its original, equilibrium value over 10^3 - 10^4 seconds as a function of the logarithm of time. This phenomenon is the signature of *slow dynamics (SD)*. SD were first observed in relatively homogeneously elastically nonlinear materials, such as rock and concrete, that have a small volume of elastically soft constituents distributed within a rigid matrix (e.g., grains in a rock), e.g. [2], and has more recently been show to exist in a broad range of solids [10]. In contrast, in damaged materials slow dynamics are due to localized nonlinear elastic features, e.g., a crack [10] and the behavior can be effectively applied for damage diagnostics [10].

The process of SD recovery can be easily observed by applying measured resonance responses (RUS measurements) at successive times after large-amplitude wave excitation, as well as by observation of the pure tone signal variation. Both methods are described below.

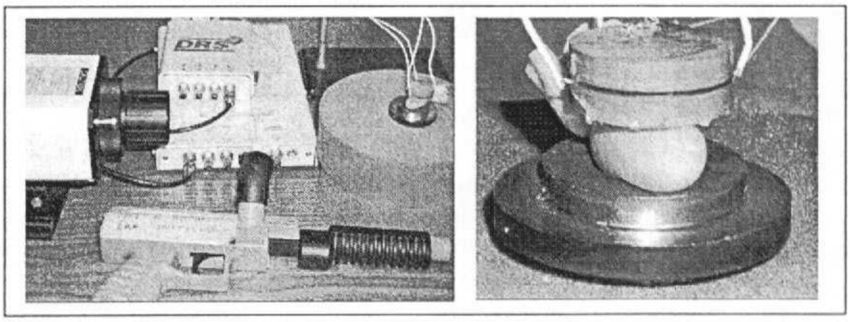

FIGURE 6. Configuration for SDD measurements.

In this variation of the SDD method we take advantage of both the amplitude and frequency of the recovery of a sample mode. The experimental setup was essentially non-contact. A water-filled bladder was used to couple the ceramic for driving the combination excitation/probe wave source. An airgun was used to induce the elastic nonlinear response. The probe-wave frequency-sweep was accomplished using the resonant ultrasound spectroscopy device manufactured by DRS, Inc. A Polytech laser vibrometer was used to detect the signal. In SDD, the equilibrium, low amplitude (linear) amplitude frequency response of the sample is first measured. The sample is then driven at large strain amplitude (order 5 microstrains) to induce material softening. Immediately upon termination of the drive, the RUS measurement recommences at very low strain amplitude (order microstrain) for monitoring the recovery.

Results of the swept-tone tests using the airgun source are shown in Figure 6. We see in the left hand figure an uncracked—but still elastic nonlinear—sample. The sample at right is damaged. We see this by the large change in frequency and the successive recovery. The sample recovery time shown is 141 seconds. Full recovery took approximately one hour. Clearly it is only necessary to look at one or two probe sweeps to discern whether or not the sample is damaged so the method can be applied relatively quickly.

Monitoring SD recovery is interesting from a basic research perspective and in some instances is fast enough to apply for typical NDE applications. For quick application, a variation of the SDD method known as the slope amplifier may more appropriate. Figure 7 describes how the SDD slope amplifier works, and Figure 8 shows SDD slope amplifier results obtained from an automotive bearing cap.

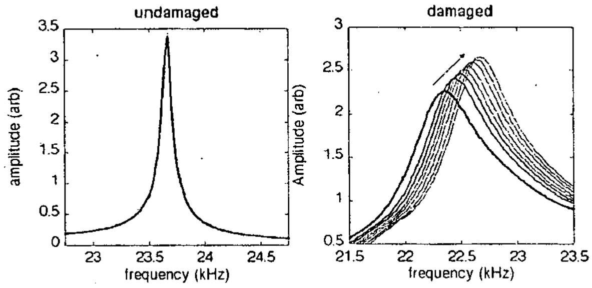

FIGURE 7. Resonance response of a mode in an undamaged sample and the recovery process of SD in a damaged sample.

In summary, we have described two Nonlinear Elastic Wave Spectroscopy (NEWS) methods as applied to NDE. These are Nonlinear Resonant Ultrasound Spectroscopy (NRUS) and Slow Dynamics Diagnostics (SDD). The companion paper in this volume [12] presents Nonlinear Wave Modulation Spectroscopy and Nonlinear Time Reverse Acoustics.

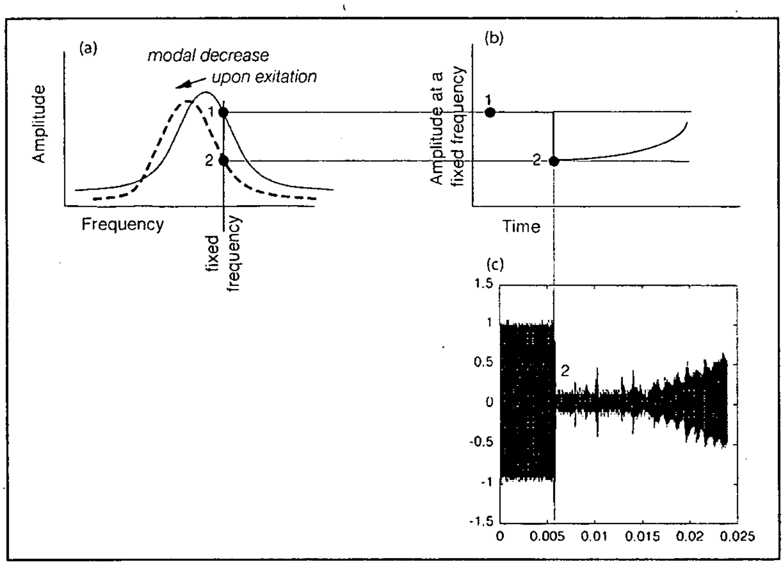

FIGURE 8. Variation on the SDD technique: the slope amplifier. (a) A low-amplitude probe-signal excites the sample near a modal peak. The signal amplitude at 1 is controlled by the modal structure. The time-average amplitude behavior of the time signal is shown in (b). The sample is disturbed by a large amplitude signal induced by a tap for instance, and the modal peak shifts downward causing the probe wave amplitude to change in amplitude to position 2 in (a) and (b). Slow dynamics keeps the modal peak diminished in frequency so that the amplitude change of the probe is pronounced. An actual example of SDD applied to a damaged solid is shown in (c).

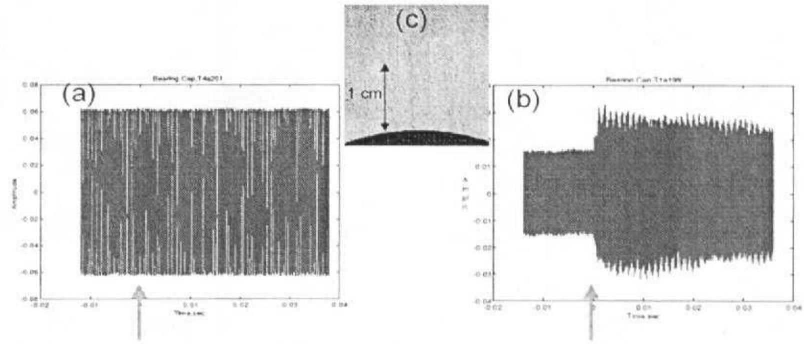

FIGURE 8. Slope amplifier results in an undamaged (a) and cracked (b) automotive bearing cap. The crack is shown in (c). Note that in this experiment, the probe was located lower than the resonance peak and therefore the amplitude increases when impacted by the airgun. Arrows point to the time of impact. The data were high-pass filtered.

ACKNOWLEDGEMENTS

This work is supported by Institutional Support (LDRD) at Los Alamos.

REFERENCES

1. Ostrovsky, L. and Johnson, P. A., *La Rivista del Nuovo Cimento.* **24**, 1 (2001).
2. Guyer, R. and Johnson, P. A., *Physics Today.* **52**, 30 (1999).
3. Johnson, P. A., *Materials World, J. Inst. Materials.* **7,** 544 (1999).
4. Buck,O., Morris, W.L. and Richardson, J.N., *Appl. Phys. Letters* . 33, 371 (1978).
5. Cantrell, J. H., Yost, W.T. *Philosophical Magazine A-Physics of Condensed Matter Structure Defects And Mechanical Properties.* **69**, 315 (1994).
6. Barnard, D.J., Dace, G.E., Buck, O. *Journal of Nondestructive Evaluation.* **16**, 67 (1997).
7. Zheng, Y.P., Maev, R.G., and Solodov, I.Y., *Canadian Journal of Physics.* **77**, 927 (1999).
8. Kourtiche, D., Ait, L., Allies, L., Nadi, M., and Chitnalah, *A., Meas. Sc. Techol.* **15,** 21 (2004).
9. Korotkov, A.S., Slavinsky, M.M., Sutin, A.M. *Acoustical Physics.* **40**, 84 (1994).
10. Johnson, P. A., B. Zinszner, Rasolofosaon, P. N. J. , *J. Geophys. Res.* **101**, 11553 (1996).
11. Van Den Abeele, K. E.-A., J. Carmeliet, J. TenCate and Johnson, P. A., *Research on NonDestructive Evaluation* **12**, 31 (2000).
12. Johnson, P., Sutin, A. and TenCate, J., *World Congress on Ultrasonics* ed. P. Laugier (2003) p. 129.
13. Johnson, P. and A. Sutin, A., *J. Acoust. Soc Am.*, in press (2004).
14. Sutin, A., Johnson, P. and TenCate, J., *World Congress on Ultrasonics,* ed. P. Laugier (2003) p. 121.
15. Sutin, A. and Johnson, P. A., in *Review of Progress in QNDE*, eds. D. O. Thompson and D. E. Chimenti, Plenum, New York, this volume (2004).
16. Guyer, R., McCall, K., Boitnott, G., Hilbert, B. and Plona, T., *J. Geophys. Res.* **102**, 5281 (1997).
17. Migliori, A. M.. and Sarrao, J., "Resonant Ultrasound Spectroscopy", John Wiley, 1997.