NEW NONLINEAR ACOUSTIC TECHNIQUES FOR NDE

James A. TenCate
Los Alamos Seismic Research Center, EES-4,
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract. Acoustic nonlinearity in a medium may occur as a result of a variety of mechanisms. Some of the more common nonlinear effects may come from: (1) one or several cracks, volumetrically distributed due to age or fatigue or single disbonds or delaminations; (2) imperfect grain-to-grain contacts, e.g., materials like concretes that are "cemented" together and have less than perfect bonds; (3) hard parts in a "soft" matrix, e.g., extreme duty materials like tungsten/copper alloys; or (4) atomic-scale nonlinearities. Nonlinear effects that arise from the first two mechanisms are considerably larger than the last two; thus, we have focused considerable attention on these. The most pervasive nonlinear measure of damage today is a second harmonic measurement. We show that for many cases of interest to NDE, a second harmonic measurement may not be the best choice. We examine the manifestations of nonlinearity in (nonlinear) materials with cracks and/or imperfect bonds and illustrate their applicability to NDE. For example, nonlinear resonance frequency shifts measured at increasing drive levels correlate strongly with the amount of ASR (alkali-silica reaction) damage of concrete cores. Memory effects (slow dynamics) also seem to correlate with the amount of damage.

INTRODUCTION

A frequently used nonlinear measure of damage for an NDE application is obtained by measuring the second harmonic generated within a sample. This measure is usually quantified by a single parameter, $\beta$—the coefficient of the next term of a power law expansion of the linear equation of state. Quantifying nonlinearity in this way is a natural first choice, likely suggested by the nonlinear acoustics literature of the late 1800s [1]. With care—harmonics caused by the measurement system itself are hard to eliminate—$\beta$ appears to correlate fairly well with the amount of damage for some applications.

Using $\beta$ as a damage indicator, however, does not work in every instance. In the last decade, experimental studies [2–5] of rocks and other geomaterials (e.g., damaged concrete) found that many different values for $\beta$ were possible for the same sample or that $\beta$ did not change with increasing damage. For example, values of $\beta$ for several concrete samples seemed to correlate poorly with amount of ASR (alkali-silica reaction) damage determined by other methods [6]. Furthermore, sometimes surprising and counterintuitive values of $\beta$ have been reported in the NDE literature [5,7] as well. In this paper we suggest that for a volumetrically damaged material (e.g., fatigued or aged materials) there are other manifestations of nonlinearity which are much easier to observe and measure; these are proving to be far more sensitive indicators of damage than $\beta$[5]. Thus, we first examine various manifestations of nonlinearity (in ASR-damaged concrete) and illustrate, in a qualitative fashion why a second harmonic measurement is not the best choice for discerning damage in these materials. We then conclude by suggesting some alternative measures that may prove to be valuable NDE tools in the future.
VARIOUS MANIFESTATIONS OF NONLINEARITY

In many nonlinear systems, nonlinearity (whatever its cause) produces harmonics as waves propagate. As already noted above, measuring the amount of second harmonic present is often used to determine the amount of damage in a sample. However, the effects of nonlinearity on wave propagation are quite diverse and a simple second harmonic measurement may not be the right choice; it may, in fact, lead to the wrong answer! What follows are descriptions of two experiments which both show that $\beta$ does not give a complete picture of the nonlinearity.

Wave Propagation in a Damaged Material

A wave propagation experiment was performed and compared with a simple lossless nonlinear theory. Similar to what is often done in the NDE literature, the linear wave equation (for one-dimensional motion along a long thin bar) was modified to take nonlinearity into account by adding additional terms (in a power series expansion) to the stress-strain relation [4]. A nonlinear stress-strain relation for wave propagation in a long thin bar may then be written as:

$$\sigma = E\varepsilon (1 + \beta \varepsilon + \delta \varepsilon^3 + \cdots)$$  \hspace{1cm} (1)

where $\sigma$ is the stress, $\varepsilon$ is the strain, $E$ is Young's modulus, and $\beta$ and $\delta$ are coefficients of the next (higher order) terms in the expansion. Equation (1) together with a force equation (Newton's second law) and the equation of continuity (conservation of mass),

$$\rho_0 \ddot{\xi}_x = \sigma_x$$  \hspace{1cm} (2)

$$\varepsilon_i = u_x$$  \hspace{1cm} (3)

can be solved using the method of characteristics [8,9]. Here $\rho_0$ is the unstrained mass density, $u$ is the velocity, and $\xi$ is the displacement. The characteristics solution can be implemented numerically and waveforms calculated for various propagation distances.

A qualitative experiment was performed where a fairly low frequency pulse of several cycles of 10 to 20 kHz tone was sent down a 2 m long, 2 cm diameter thin (but damaged) cylindrical rod; the motion is nearly 1 dimensional. The pulse waveform was received by a B&K accelerometer mounted 60 cm from the source, oriented in the propagation direction, and mounted to the surface of the sample [10]. Corresponding theoretical waveforms for this experiment were calculated using the characteristics solution [11] (a 12 line MATLAB script) for a wave propagating within a nonlinear material with each of only one of the nonlinear terms present ($\beta$ or $\delta$).

Results of the experiment and comparison with the simple lossless theory are shown in Figure 1. Comparison of the theoretical waveforms with the experimental measurements show that the measured waveforms appear to be dominated by $\beta$ in the left two cases, (a) and (b), and by $\delta$ for the right two cases, (c) and (d). Note that choosing only slightly different source frequencies for this experiment will yield different values of $\beta$. Resonance measurements in damaged materials further demonstrate the variability of the nonlinear response and will be presented as the next example.
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Resonance measurements in a damaged material

Consider a simple resonance experiment on a core sample of alkali-silica-reactivity (ASR)-damaged concrete [12]. The samples were approximately 12 cm long and 2 cm diameter. Unlike a usual resonance inspection technique, only the lowest order longitudinal mode (around 10 kHz) was studied. Drive frequencies were swept through and past the resonance frequency (and back again) and the resulting response recorded for several different drive levels. Figure 2 shows distinctive changes in the resonance curves as drive level was increased: the resonance frequency shifted downward, the curves took on an unusual asymmetry, and up/down curves traced different paths. Such unusual resonance curves cannot be obtained from a sample described by a simple $\beta$-only power law

FIGURE 2. Young’s mode resonance curves taken at successively higher drive levels for an ASR damaged concrete sample. Downward shifts in resonant frequency and increasing asymmetry are both evident with increasing drive level. Memory effects are also visible: upward sweeps (solid lines) differ from downward sweeps (dashed lines).
POTENTIAL NEW NONLINEAR NDE TOOLS

The above examples suggest that there might be other nonlinear measurements (other than a second harmonic measurement) which might be used to detect damage. Two such measures are now proposed and described.

Nonlinear Frequency Shifts

One new nonlinear measure of damage suggested by the above is to construct a plot of resonance frequency versus drive level (or strain). More damage should lead to larger frequency shifts for the same strain. To demonstrate, resonant frequency peak shifts as functions of strain were plotted for two different concrete cores taken from the same section of aged highway roadbed. One sample—its resonance curves are shown in Fig. 2—shows clear indication of ASR damage, the other appears to be intact with very little evidence of ASR damage. Both samples share similar geometries and are of comparable sizes. The peak shifts vs strain data are shown in Fig. 3. Both concretes show a clear increase in peak shift with increasing drive. However, the ASR-damaged sample shows nearly an order of magnitude larger frequency shift at the same strain. Other examples of application of this method to NDE problems can be found in Ref. [5].

An even simpler and faster measurement for part sorting applications would be to examine an interesting mode (or several) at just two different levels, one response taken at
very low amplitude and another at larger amplitude. No peak shift would indicate an undamaged part while a large peak shift would indicate some sort of damage.

**Nonlinear Memory Effects**

As noted above, damaged materials also exhibit memory effects. When a moderate strain is applied to a sample the resonance frequency drops (see Fig.2). However, when the strain is removed, the resonance frequency (and modulus) do not immediately return to the value they had before the excitation was applied. Rather, the return can take minutes to hours depending on the sample and the exact nature of the applied strain. Figure 4 shows plots of resonance frequencies as a function of log(time) for 6 very different samples after the applied strain was removed.

Remarkably, despite the striking differences in the microstructure and chemistry and “damage” found in these samples, the recoveries all go as log(time). Recent additional measurements [15] have shown remarkably universal log(time) behavior in these materials.

The above observations suggest another new nonlinear measure of damage. Plotting the recovery of a sample should nicely correlate with the amount of damage. To demonstrate, measurements were made on the two concrete samples described earlier. A moderate drive level—approximately 1 microstrain—was applied to each for 5 min near the resonance frequency of each sample (approximately 7 to 10 kHz). The drive was then turned off and the resonance frequency tracked by use of a very small amplitude swept source probe and a lock-in amplifier. In each case, the sample recovered as log(time) for approximately 20 to 30 minutes. The recovery slowed somewhat after that.

Figure 5 shows data taken from the experiment described above. Per unit of measured strain, the recovery slope of the damaged concrete is far steeper than that of the intact sample. The quality of the data and ease of determining the slope of the data suggest it as an excellent candidate for damage evaluation for this particular application. Recent measurements show that the residuals from a linear fit to data are only $1 \times 10^{-6}$ of the asymptotic value!

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**FIGURE 4:** Resonance frequency recoveries from a moderate drive level. Samples include concretes, a limestone, and various sandstones. All show remarkably similar behaviors.
DISCUSSION

The experimental results shown here suggest that some care is needed in using nonlinear measurements for damage evaluation. The nonlinear response for common, volumetrically damaged samples is far more complex that one might initially expect. The presence of memory effects can, in fact, seriously affect standard nonlinear measurements and techniques based on simpler models. However, the additional complexity shown here affords the opportunity to develop more tools that should prove valuable to future NDE work.

As suggested by their similar nonlinear responses, materials with volumetric damage appear to be likely candidates for some of the new nonlinear NDE measurement techniques outlined here and elsewhere [5,16]. Although the exact nature of the cause of these effects is unknown, a likely candidate mechanism for the effects seen here is a form of creep. Further understanding of the process and its relation to the types of damage likely to be encountered in NDE applications will be helpful in designing which nonlinear measures will be best suited to these new methods.

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