Nonlinear Wave Modulation Imaging

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Abstract. Discerning the location of damage features in the presence of other wave scatterers (spheres, voids, etc.) presents a difficult problem. It is an important issue from the standpoint of developing nonlinear tomographic imaging, and of nonlinear damage diagnostics and progressive damage diagnostics in general. This work illustrates that, by applying nonlinear wave means, we can create nonlinear-wave reflection-profiles with remarkable sensitivity to damage, and in doing so, distinuish between damage and other wave scattering features that are unrelated to damage.

INTRODUCTION AND BACKGROUND

It is well established that the sensitivity of nonlinear acoustical methods to the appearance and progression of material damage is orders of magnitude higher than that of conventional acoustical testing methods [1, 2, 6]. This is because it is the damage contained in a solid that creates nonlinear response, at whatever scale the damage exists be it atomic, meso, or macro in scale [2]. At the same time, locating the damage in a solid is not well developed. Developing nonlinear wave imaging methods will provide a new tool in discerning not just localized damage regions, but volumes of relative damage.

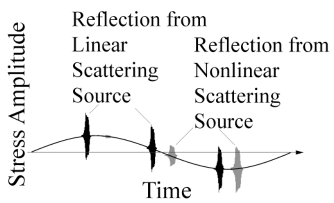

FIGURE 1. Low-frequency *cw* modulation of successive ultrasonic pulses in a material containing a linear and nonlinear scatterer.

Work recognizing a relationship between damage and nonlinear dynamic wave response by study of the wave second harmonic was performed as early as 1979 [3]]. Variations of the second harmonic method for diagnosing the presence of damage have since been described in numerous articles, e.g., [4]. More recently it has been demonstrated that the second harmonic is not nearly as robust in detecting damage as are applying manifestations of "nonclassical" nonlinearity [1]. "Nonclassical" nonlinearity arises from hysteresis in the wave pressure-deformation (stress-strain) response, *due to*

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the presence of damage [5]. ”Low-aspect ratio” (flat) features like cracks, grain contacts, delaminations, etc., create nonclassical nonlinear wave effects. Other geometries (spheres, holes, ellipses, surfaces, etc.) do not.

A low frequency, continuous wave excitation is applied to the specimen simultaneous to a group of high frequency tonebursts. Due to the vibration, the amplitude and phase of the ultrasonic toneburst reflected from a crack will be modulated, while the signal reflected from a linear defect (a hole, a material boundary for instance) has no modulation. One can see the difference schematically in fig. 1. The figure shows tonebursts reflected from a linear and nonlinear scatterer, respectively, at different times, in the presence of the vibrational-induced stress field.

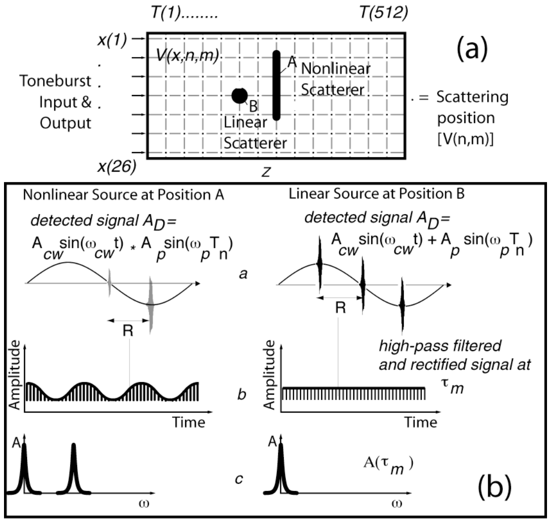

FIGURE 2. (a) conceptual view of the experiment and (b) processing scheme.

We have developed a manner that employs the above concept, while simultaneously eliminating all other wave scatterers in the detected signal other than nonlinear ones. The method is accomplished by use of a strobe (equivalent to a lock-in amplifier) in the detecting digitizer. By way description, fig. 2 shows schematically how a signal is processed, and illustrates an example from a region at the crack (A in the figure) and one at the hole (B). By progressively increasing the strobe delay detecting the ultrasonic signal, the behavior at discrete locations along the wavepath can be recorded. Further, by moving the detector and the toneburst source along the sample face, signal response can be captured at potentially all points in the 2-D/3D space in the sample.

There are a sequence of important time scales in the experiment. For source locations $x_1 \cdots x_i, i = 26$ a tone burst of 3MHz and duration 0.66μsec is launched at a sequence of times, $T_1 \cdots T_N(x), N = 512$, where

$$T_n(x) = \frac{1}{366}(n-1)\, sec, \quad n = 1 \cdots N. \tag{1}$$

METHOD

The detected signal in the time intervals $T_n \leq t \leq T_n + \Box T$ are recorded, (rectified, and digitized at rate 0.6μ sec, i.e., $\Box T = 256 \times 0.6\mu$sec. As a consequence the output is an ”amplitude” matrix

$$V_{nm}(x) = V(T_n, \Box_n), \tag{2}$$

where $\square_n = m\square_0$, $256\square_0 = \square T$, $m = 1\cdots256$, and $n = 1\cdots N$. The basic analysis is to study the Fourier structure of $V(T_n, \square_n)$ at fixed $\square_n$,

$$A(\square_n, x) = \square_{n=1}^{N} V(T_n, \square_n) \sin \square T_n, \tag{3}$$

where the low frequency modulation signal, the 10Hz signal, is $sin\square t$.

This procedure will identify those $\square_n$ at which the detected signal has evidence of the nonlinear scatterer. The associaltion of time with space is an activity that can be carried out independently of the experimental procedure, so the above steps don't depend on this identification. If $t \square z$ in some known way the output can be used to identify the location of the nonlinear scatterer. The full wave profile is obtained by iterating the above steps at each source position (x). The full output data set from the experimental and processing procedure is an $X - T$ matrix of amplitude values V The sample used to demonstrate the NWMS imaging technique was a steel plate of dimension 50 x 305 x 6 mm containing a crack and hole as shown in fig.3. The ultrasonic toneburst wave was radiated at the plate face as shown in the figure. Triggering was accomplished by using the electrical toneburst applied to the transducer. The far end of the plate was connected to a mechanical shaker.

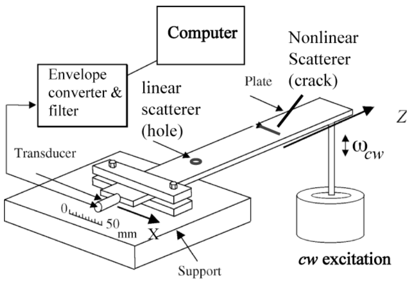

FIGURE 3. Experimental configuration.

RESULTS AND DISCUSSION

For comparison, a standard pulse echo experimental result was conducted as well. The reflection profile of the standard pulse-echo and that of the nonlinear response are shown in figs. 4a,b. In fig. 4a, it is clear that the amplitude of the linear signal reflected from the hole is higher than the amplitude of signal reflected from the crack. Both features are imaged, but the nature of the features is unknown without a priori knowledge or some other means of testing. In the case of the nonlinear reflection profile the level of the modulation in the signal reflected from crack is large (fig.4b). The hole is a linear scatter and therefore should not produce modulation of the reflected signal. The hole does create some signal for reasons not yet clear, but the difference between the two reflection profiles is impressive. This experiment clearly demonstrates that a crack can be discriminated within the background of linear scattering from inhomogeneities other than cracks, and including sidewall and backwall reflections.

Figure 5 compares the detected amplitude from the crack for the wave modulation method (double peak) and a standard (linear) pulse echo measurement. The crack tips are predominantly imaged, and indicate that the crack tips are primarily responsible for nonlinear scattering.

This work demonstrates that the toneburst modulation technique is a novel tool for nonlinear acoustic imaging of defects, even in the presence of "linear" scatterers unrelated to damage. The results imply that the method could be applied to careful study of the spatial distribution of nonlinear crack properties. Such studies may shed light on such issues as crack initiation, crack progression, and the physical origin of nonlinear behavior.

From numerous other studies conducted by us and others, we know that different volumes can display different nonlinear characteristics. This method is applicabable to study of mixed volumes where such differences may exist. Conceivable applications include imaging of mixed phase materials, imaging of progressive fatigue of volumes where the fatigue may not be homogeneous, and surface seismic and borehole applications.

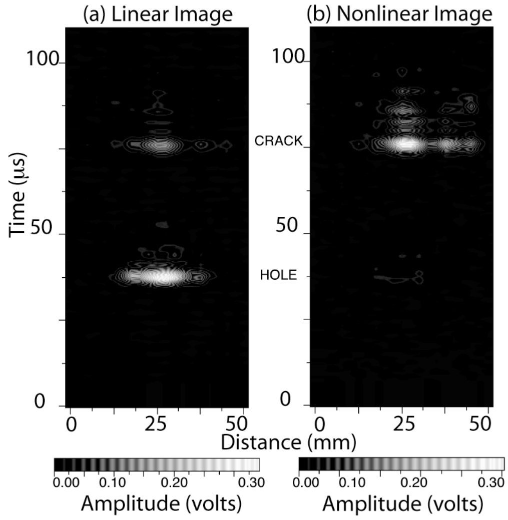

FIGURE 4. Elastic linear scattering profile where the reflection from the hole is at 35 microseconds. The crack is the later, less strong reflection. (b) Nonlinear profile where crack is imaged. Lighter regions correspond to larger scattering response.

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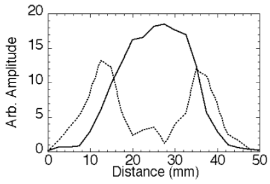

FIGURE 5. See text for explanation.