DEVELOPMENT OF NONLINEAR SLOW DYNAMICAL DAMAGE DIAGNOSTICS (S3D) FOR APPLICATION TO NONDESTRUCTIVE EVALUATION

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Abstract
The onset and monitoring of the nonlinear material response called *slow dynamics* can be applied for expedient damage interrogation. The method, called *Slow Dynamical Damage Diagnostics (S3D),* is based on applying a low-amplitude, pure or swept-frequency probe-signal near or on an eigenmode of a sample. The sample is then mechanically excited by a larger amplitude signal, and, if damaged, material softening and slow dynamics are induced (elastic nonlinear response), changing the probe-wave amplitude and frequency characteristics. A change in the probe wave characteristics can be used to directly infer that a material is damaged. We describe two versions of S3D. We also include several novel, non-contact methods of wave excitation that could be applied to other techniques.

Introduction
When a member of the class of materials known as "nonclassical" or "nonlinear mesocopic" [1,2] 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 wave speed decrease and the creation of harmonics and wave modulation. Simultaneously, the material modulus and the quality factor (specific dissipation, Q) decrease. We call this behavior "nonclassical nonlinear fast dynamics" (NNFD) [3]. NNFD is distinguished from "atomic" acoustic/elastic nonlinearity in liquids, most metals, individual crystals, etc., [4] by extreme nonlinearity and hysteresis in the stress-strain relation (the equation of state). NNFD materials exhibit characteristic scaling relations of, for instance, harmonic amplitudes, with applied strain that are different from atomic elastic materials [4-8].

The NNFD materials do not immediately recover to their original states. Instead, they recover to their original, equilibrium values over 10^3 - 10^4 seconds as a function of *log(t)*. This phenomenon is the signature of *slow dynamics (SD)*. SD were first observed in relatively homogeneously 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. [9]. In contrast, in damaged materials slow dynamics are due to localized nonlinear elastic features, e.g., a crack [3]. In this work we take advantage of the transition region of NNFD/SD, where fast dynamics dissipate quickly but slow dynamical response persists, as a quick and sensitive damage diagnostic. We call this the method of Slow Dynamics Damage Diagnostics (S3D). Our purpose here is to describe two versions of S3D that are most appropriate for application to high Q and low Q materials, respectively. In order to describe the methods, we will also present brief descriptions of SD characteristics.

Methods and Results
S3D With a Pure Tone.
The method is based on applying a pure tone probe signal near an eigenmode of a sample. When the sample is disturbed by a larger amplitude signal, the eigenmode abruptly shifts, changing the probe-wave characteristics and simultaneously inducing slow dynamics [3]. Such a change in amplitude only occurs in damaged materials.

The experimental configuration is shown in Figure 1.

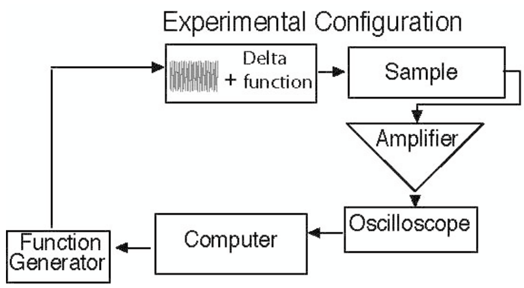


Figure 1: Experimental configuration for pure-tone S3D.

In the measurement a relatively high-amplitude impulse (strain~$5x10^{-5}$) is used to produce nonlinear material softening in the presence of a crack, and induce the SD. The impulse is delivered by a mechanical excitation in this case (equivalent in energy to a tap with a pencil). A low-amplitude (strain~10^{-7}), pure-tone probe is input into the sample to monitor material change before, during and after the impulse. As noted, due to material softening the effect on a given mode in a nonlinear material upon excitation is to shift the modal frequency downward, as illustrated in Figure (2) [bottom]. As a result of the mode shift, the probe shows a significant amplitude change (2 in Figure 2, top): it is a slope amplifier. The shift remains for some time due to the effect of slow dynamics and is therefore easily observed well after the impulse excitation has dissipated. Slope amplification and the persistence of SD make the method very powerful.

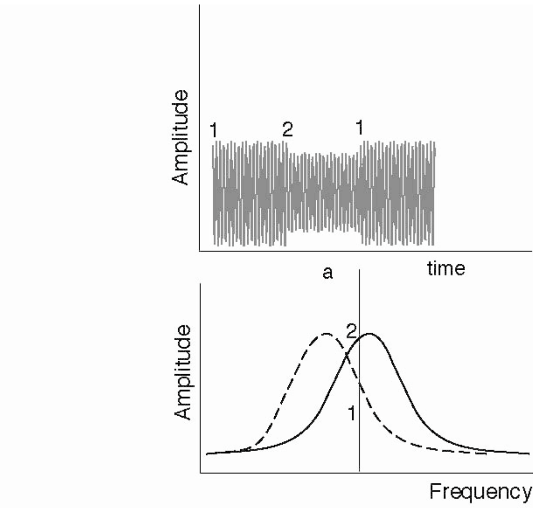


Figure 2: Conceptualized material softening and the application of the slope amplifier. The bottom plot shows an eigenmode frequency shift before and after excitation (solid line and dashed lines, respectively). The pure-tone probe is indicated by the solid line. The top plot shows the corresponding effect on the probe time series. The probe wave (1) is undisturbed until the disturbance. At the time of the disturbance (2), the eigenmode shifts and the amplitude correspondingly changes (1-»2 bottom plot). With time the material returns to its original state (1). The transition time (2) marked by the probe-wave amplitude change is used for S3D.

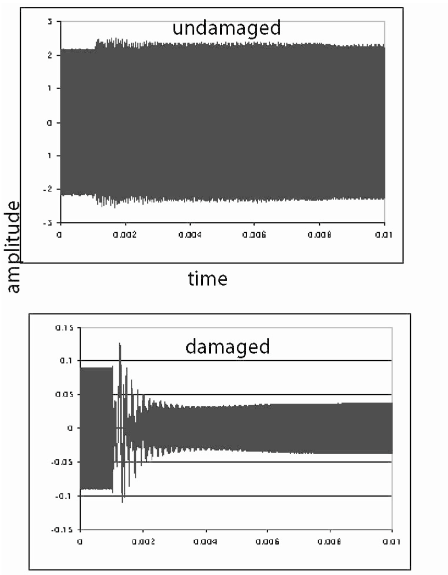


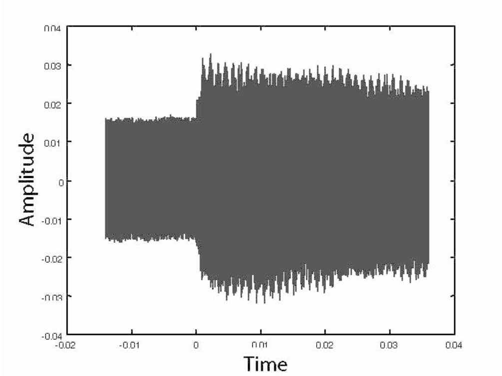
Figure 3. The slope amplifier at work. The *x*-axis is time, and the *y*-axis is amplitude. The damaged sample is easily identified due to the significant amplitude change. The method can be quickly applied because all that is required is to view whether or not an amplitude change takes place.

Thus what is observed in the experiment is dependent on the location of the fixed-frequency with respect to the eigenmode peak. By judicious choice of the fixed frequency (e.g., near the mode inflections), we gain significantly in our ability to observe the onset of SD in materials that have relatively narrow modal peaks, corresponding to low values of dissipation.

In a simplistic manner, the amplification is proportional to the specific dissipation Q. We find $\Delta A = abs(CQ\Delta f)$, where C is a constant relating Q and Δf. Meaning there is an amplification by CQ in sensitivity over the frequency shift. With increasing Q the slope of the resonance curve steepens, making the slope amplifier more effective. At low Q, the method works less well because ΔA becomes relatively smaller. Because the probe can be placed on either side of the modal peak, the sign of the amplitude change is probe-frequency dependent, so ΔA(f) is its absolute value [4].

Figure 3 illustrates results from application of the method to otherwise identical automotive bearing caps, one undamaged (top) and one containing a small crack (bottom). In the bottom figure the damaged sample contains a small crack order 2x2mm. The probe wave was applied by a small (0.7 cm) ceramic transducer. The large amplitude excitation was induced by a small hammer impact. In the figures, the probe wave is observed before impact, at impact

Figure 4. The slope amplifier results in a sample applying a probe-wave frequency that is lower in frequency than the eigenmode peak.



(clearly seen by the amplitude change in bottom figure), and post impact. Note the signal due to the impact and the associated ringing. The ringing dissipates but the amplitude change remains due to SD (not indefinitely: the material returns to its original state after some time). The probe frequency is located on the right-hand side of the modal peak as illustrated in Figure 2, and this is why the probe-wave amplitude decreases with the disturbance, in contrast to the next example.

Another example of the of *S3D* application using the same material, but with a different probe frequency is shown in Figure 4. Here the probe wave amplitude increases from the large amplitude disturbance

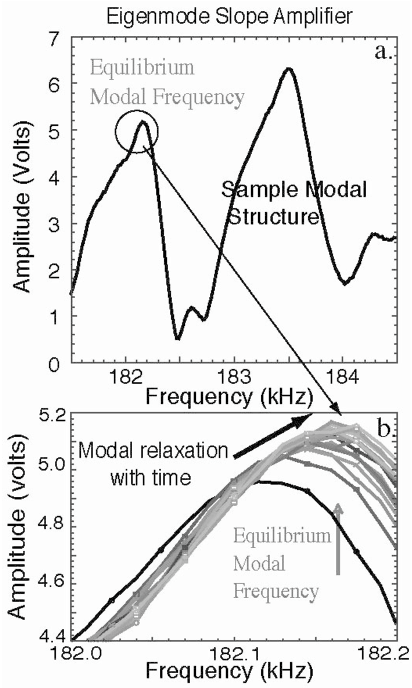


Figure 5: The slope amplifier employing a swept tone for application to S3D.

because the probe is located on the left-hand side of the modal peak, in contrast to the previous example. Note that the method does not introduce additional damage because the wave disturbances applied are small, comparable to standard acoustical/ultrasonic wave NDE methods.

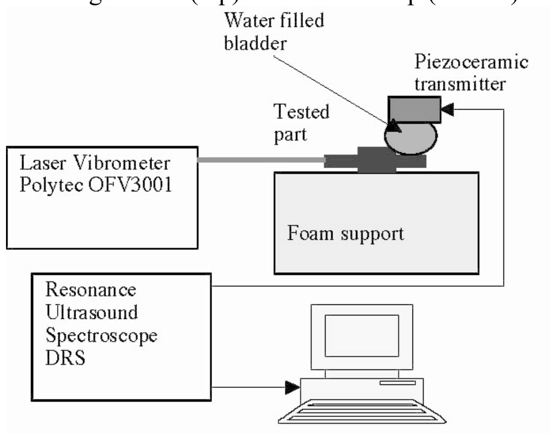
Numerous samples have been successfully tested with this version of S3D, including manufacturing components of many types and at many stages in their respective manufacturing stages, disbonding in composites and two layer systems, etc.

S3D Using a Swept Mode Probe.

In this variation of the method we take advantage of both the amplitude and frequency of the recovery of a sample mode. The method is identical to that employing the pure tone probe except that a frequency-swept tone is used. Figure 5 illustrates the concept. In (a) a measured modal spectrum of a sample is shown. In (b), an expanded view of modal peak circled in (a) is shown, before excitation and during recovery. The various curves are individual frequency sweeps made at successive time intervals. They illustrate the progressive relaxation of the modal peak back to its equilibrium state shown in (b) (the vertical arrow). The method employing a swept tone works particularly well in situations when the material itself is elastically nonlinear, but also contains a crack.

An example using a "green" manufacturing part (the first stage in the part's manufacture) will be shown as an example. The experimental setup, shown in Figure 6, was essentially non-contact. A water filled bladder

Figure 6: Apparatus for swept-probe: Experimental configuration (top). Photo of set-up (bottom).



was used to couple the ceramic, probe wave source from the sample. An airgun was used to induce 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. Independent of the S3D method, the non-contact sources developed here are extremely useful and could be applied to

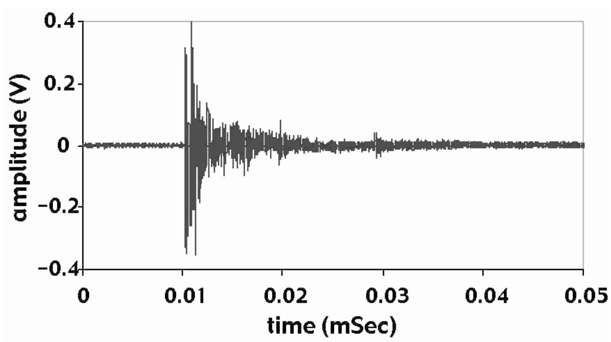
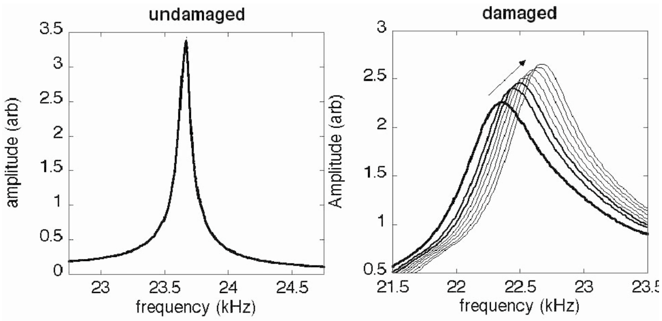


Figure 7. Airgun excitation of sample.

other linear and nonlinear methods. Figure 7 shows how energetic the time signal is from the airgun.

Results of the swept-tone tests using the airgun source are shown if Figure 8. 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

Figure 8. Results of the swept-tone version of S3D in a green manufactured part.



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. In this case, one has both the frequency had amplitude However, tracking initial frequency shift during fast dynamics and the recovery of a modal peak is extremely robust.

Conclusions

We have described two variations of a new damage diagnostic tool. The method, called Slow Dynamics Damage Diagnostics, is quick and relatively simple to apply. We also have described a novel non-contact means of probe-wave and impulse-wave excitation that could be applied elsewhere. It is important to note that the methods do not introduce additional damage (at the macroscale). The wave disturbances applied are small and comparable to most acoustical/ultrasonic wave NDE methods. Our experience is that these may be the most sensitive damage diagnostic tools available.

Acknowledgements.
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