The new wave in acoustic testing

Nonlinear wave methods for examination of damage in materials are the new frontier of acoustical nondestructive testing, offering previously unimagined sensitivity, speed of application, and ease of interpretation, as Paul Johnson reveals

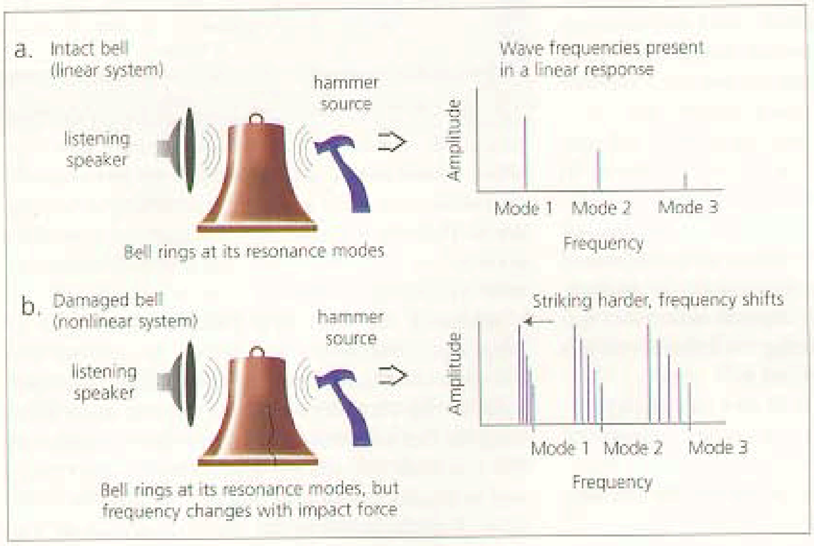
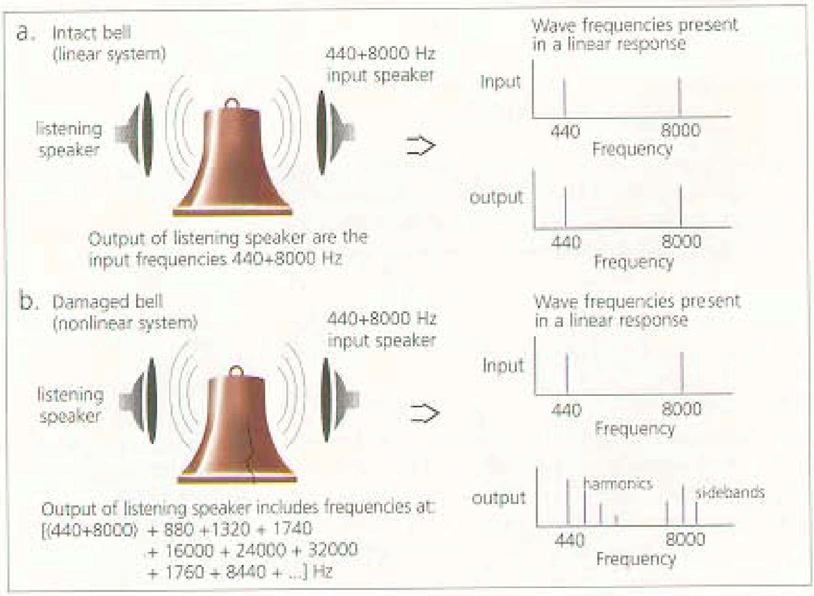


Figure 1
Illustration of linear versus nonlinear wave resonance behaviour in a bell

Strike a bell, and the bell rings at its resonance modes. Strike it harder and the bell rings at the same tone, only louder. Now imagine a small crack in the bell, perhaps invisible to the eye. We strike the bell gently and it rings normally. Striking it harder we find, to our surprise, that the tone drops in frequency ever so slightly. Striking it even harder, the tone drops even further down in frequency. This frequency shift is a manifestation of nonlinearity due to the presence of the crack.

Figure 1 illustrates how the bell responds elastically linearly when undamaged, but elastically nonlinearly when damaged. The bell behaves in an expected manner when intact, figure 1a – ringing the bell with a hammer excites the resonance modes of the bell, giving rise to a frequency spectrum in which only the resonance modes are present. If the bell has even a very small crack present, the modal frequencies depend on how hard the bell is struck, figure 1b. This is a nonlinear effect – a change in wave frequency with wave amplitude. We have called this method nonlinear resonant ultrasound spectroscopy (NRUS), a subset of nonlinear elastic wave spectroscopy (NEWS).

Figure 2
Illustration of linear versus nonlinear wave harmonics and modulation response in a bell



This example is taken a step further in figure 2 for the sake of illustrating additional manifestations of nonlinearity. For instance, we input 440 Hz and 8000 Hz into the undamaged bell using an audio speaker (these are arbitrarily chosen frequencies and are not crucial to the general result). Not suprisingly, the bell will ring at the two input frequencies, figure 2a. If we input the two tones into the bell when a small crack is present, interesting things happen again. We find that, not only does the bell ring at 440 Hz and 8000 Hz, but other frequencies abound, figure 2b. We also detect harmonics at two times, three times and four times each input frequency (880, 1320, and 1740 Hz; and 16000, 24000, and 32000 Hz, respectively). In addition, we detect the sum and difference frequencies between the 440 and 8000 Hz, or sidebands, of 8000±440 Hz. This method is known as nonlinear wave modulation spectrscopy (NWMS), another subset of NEWS.

The nonlinearity due to the presence of one or more cracks is an extremely sensitive indicator of the presence of damage. The undamaged portion of the sample produces nearly zero nonlinear effect. The damaged portion of the material acts as a nonlinear mixer (multiplier). It is a localised effect. Using a frequency spectrum analysis, we can easily tell the difference between an undamaged and damaged object. In fact, I am not aware of a more sensitive, more rapid, easy -to-apply method for detecting and examining material damage.

In our studies we have found that the nonlinear response of a sample provides a quick, qualitative test of pass/fail in numerous metal components such as alternator housings, engine bearing caps, various gears, Plexiglas, synthetic slates, weapons components, etc, where damage is localised. However, the elastic nonlinear response is also useful in examining the physical state of volumetrically damaged materials, such as concrete, rock core and other porous materials (including the effects of fluid saturation) and is being applied to characterise dislocations in metals, and to study progressive damage in these materials. Some of the materials that we have tested are shown in figure 3.

The general concept of nonlinear mesoscopic elasticity, can be stated as follows – as a material fatigues or is damaged, dislocations, cracks and flaws may be introduced, resulting in a significant change in the material nonlinear elastic wave behaviour. This behaviour is manifest in two primary manners when sound is applied to the object. Firstly, under resonance conditions (such as the bell), the resonance tone changes as the applied volume is increased. Second, under resonance, continuous wave, or pulse-wave excitation, frequency-mixing spectral components such as wave harmonics appear. These effects are enormous in damaged material but nearly unmeasurable in undamaged materials. They are the signatures of damage. Linear methods in acoustical nondestructive testing rely on either reflected wave energy from a crack, wave speed changes and/or amplitude changes. None of these linear wave characteristics is as sensitive as the nonlinear response of the material.

In volumetrically damaged materials, micro-features such as dislocations are responsible for the nonlinear behaviour. It is interesting that volumetric and local damage over several orders of magnitude in scale ($\sim10^{-9}$–10^{-1}), provide very similar nonlinear characteristics. That is, there are close similarities between the nonlinear response from the presence of dislocations in a sample and a single macrocrack in a sample. The similarities are currently under intense scrutiny in order to determine why this is so. Figure 4 illustrates the type of features, large and small, that lead to a large nonlinear wave response under wave excitation. Dislocations in Type 2 diamond and sapphire, a single crack in a ceramic (barium magnesium silicate doped with borosilicate glass), a crack in sandstone, a connecting rod, a bearing cap, and concrete all lead to very similar nonlinear wave behaviours.

As a practical example we show wave mixing experiments in undamaged and damaged automobile engine bearing caps used to discern whether or not damage is present. In these tests, one high frequency wave and several low frequency waves were used simultaneously as input. Thus we would expect mixing of all waves with each other, leading to the creation of many harmonics and sidebands when damage is present. Figure 5a and 5b show the frequency wave spectrum of the undamaged and damaged samples, respectively, only around the sideband frequencies. The damaged sample is one of those shown in figure 4. It contains a crack several millimetres deep and approximately a centimetre long. Multiple frequencies were input into the sample simultaneously in continuous-wave mode, creating many sidebands. The sample in figure 5b clearly failed the pass/fail test. Note that we observed no change in linear wavespeed or wave dissipation between the two samples, despite the fact that the nonlinear response is very different.

NEWS is ideal for monitoring progressive damage in materials as well. Figure 6 illustrates such a test. A plastic rod, fixed at one end and free at the other, was shaken at its fixed end in shear until failure (indicated by the x-axis, or number of shear cycles). The linear and nonlinear behaviour was monitored at each step, and the normalised response of each is plotted on the y-axis. We see that the linear responses (in this case wave dissipation in blue and wavespeed in red)

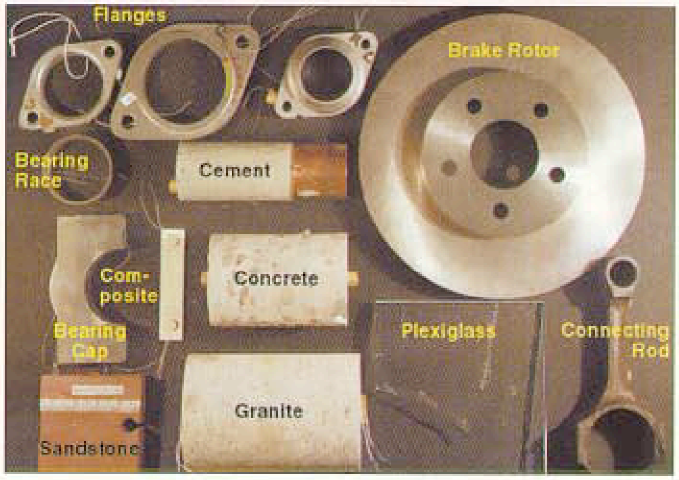


Figure 3
Various objects that have been tested for damage by use of their nonlinear response. All of the samples are damaged in some manner, either a small localised crack is present and/or the sample has volumetric damage

Diamond Sapphire

Sandstone Ceramic Concrete

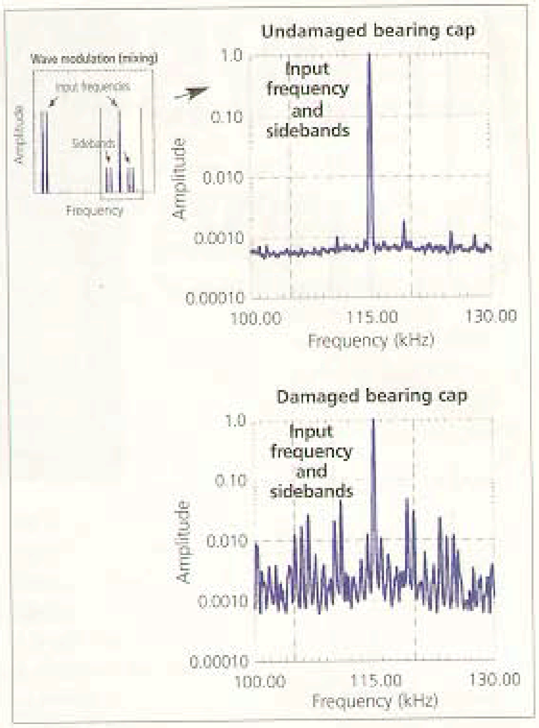
Connecting Rod Granite Bearing Cap

Figure 4
Photomicrographs and photographs showing features that can provide a nonlinear response to the bulk material when excited in a wave field

are relatively insensitive to induced damage until just before the sample fails. The nonlinear response is affected early on in the damage process, and becomes enormous very quickly. It is clear from the figure that nonlinear means are far superior to linear means in progressive damage detection.

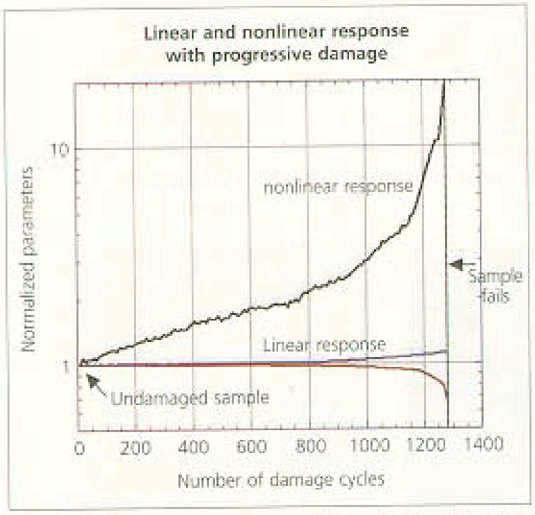
We have not mentioned other, extremely interesting, and complex nonlinear effects such as the slow dynamical response often observed. Nor have we addressed the very different nature of the nonlinearity described here compared with that of classical media (water, gas, intact materials), which have a much smaller nonlinear response and one which arises from atomic anharmonicity as opposed to the presence of damage. Nor have we mentioned the elaborate theory developed by Guyer and McCall for predicting the behaviours illustrated here. The topics just mentioned can be found in the suggested further reading section.

Figure 5
Frequency spectra from wave modulation tests of undamaged and damaged engine bearing caps. The inset (top left) illustrates a full spectrum; the boxed area within the inset illustrates the sideband portion of the spectrums shown



The instantaneous nonlinear response described here will obviously be of great interest to the nondestructive testing community. We are currently developing a method that will not only diagnose damage, but also locate the damage. NEWS represents the new frontier in acoustical nondestructive testing of materials for damage. The sensitivity of nonlinear wave methods to the appearance and progression of damage in materials is orders of magnitude larger than that of conventional acoustical methods of nondestructive testing. In fact, measurement of nonlinear behaviour may well be the most sensitive method available for study and early detection and the progression of damage. There are potentially a huge number of applications with enormous economic and safety impact that will evolve from nonlinear applications. Applications and spin-off research have and will affect a broad category of problems, from aiding design in earthquake resistant structures, to eliminating bad components fabricated on an assembly line, to monitoring long term aging in infrastructure. Further, application to structures after an earthquake may well provide valuable information regarding damage to that structure.

Figure 6
Progressive damage in a plastic, comparing the nonlinear to the linear response (courtesy of Peter Nagy)



We also believe that application of nonlinear methods, this one and others, will revolutionise nondestructive testing by providing a sensitivity to damage never before imagined. Moreover, the work may well aid the development of better, longer lasting concrete, the foundation of all building materials. We anticipate that within 10 years nonlinear methods may be routinely used in applications as diverse as quality control in manufacturing processes, quality control of concrete curing, monitoring reactor containment walls for damage, inspecting aircraft and spacecraft for damage, observing fatigue damage in buildings, bridges, tunnels, gas and oil pipe lines.

Acknowledgements

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Further reading

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- 'Nonlinear acoustics of microinhomogeneous media', V Nazarov, L Ostrovsky, I Soustova and A Sutin, *Physics of the Earth and Planetary Interiors*, 1988, **50**, 65.
- See also URL http://www.ees4.lanl.gov/nonlinear/

Paul A Johnson can be contacted at Nonlinear Elasticity, Mail Stop D443, Los Alamos Seismic Research Laboratory, Los Alamos National Laboratory
Tel: 001 505 667 8936
Fax: 001 505 667 8487
E-mail: paj@lanl.gov