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Title: APPLICATIONS OF NONLINEAR WAVE MODULATION SPECTROSCOPY TO DISCERN MATERIAL DAMAGE

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Application of Nonlinear Wave Modulation Spectroscopy to Discern Material Damage

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ABSTRACT: Materials containing structural damage have a far greater nonlinear elastic response than materials with no structural damage. This is the basis for nonlinear wave diagnostics of damage, methods which are remarkably sensitive to the detection and progression of damage in materials. Here we describe one nonlinear method, the application of harmonics and sum and difference frequency to discern damage in materials. The method is termed Nonlinear Wave Modulation Spectroscopy (NWMS). It consists of exciting a sample with continuous waves of two separate frequencies simultaneously, and inspecting the harmonics of the two waves, and their sum and difference frequencies (sidebands). Undamaged materials are essentially linear in their response to the two waves, while the same material, when damaged, becomes highly nonlinear, manifested by harmonics and sideband generation. We illustrate the method by experiments on uncracked and cracked plexiglass and sandstone samples, and by applying it to intact and damaged engine components.

1 INTRODUCTION

Experimental evidence for the highly nonlinear behavior of micro-cracked and damaged materials has existed for years from experiments of static stress-strain behavior and dynamic nonlinear wave interaction, but the methodology has yet to be developed and applied for materials testing procedures, except in rare instances.

Nonlinear elastic wave spectroscopy (NEWS) methods are powerful, new tools in interrogation of damage in materials. Due to material nonlinearity, a wave can distort, creating accompanying harmonics, multiplication of waves of different frequencies, and, under resonance conditions, changes in resonance frequencies as a function of drive amplitude. In undamaged materials, these phenomena are very weak. In damaged materials, they are remarkably large. The sensitivity of nonlinear methods to the detection of damage features (cracks, flaws, etc.) is far greater than linear acoustical methods (measures of wavespeed and wave dissipation), and in fact, these methods appear to be more sensitive than *any* method currently available. There are two general NEWS approaches to damage detection by nonlinear wave means. One NEWS method, Nonlinear Resonant Ultrasound Spectroscopy (NRUS), depends on the study of the nonlinear response of a single, or a group of, resonant modes within the material. Resonance frequency shifts, harmonics and damping characteristics are analyzed as function of the resonance peak acceleration amplitude. The method is extremely useful for basic research and specific applications that do not have strict time requirements in terms of speed of application (e.g., Johnson et al. 1996; Van Den Abeele & TenCate 1999; Van Den Abeele 1999; Byers et al. 1999). An application of the NRUS method is addressed in a companion paper (Van Den Abeele et al. 1999, this issue). The method presented here is Nonlinear Wave Modulation Spectroscopy (NWMS). This method can be quickly applied, and in our view, is ideally suited to applications where the question of damaged versus undamaged must be quickly addressed. Fundamentally, NWMS is based on monitoring nonlinear wave mixing in the material. The manifestations of the nonlinear response appear as wave distortion and accompanying wave harmonics, and in sum and difference frequency generation (sidebands). The approach has proved to be time efficient and effective in discerning damage to materials in our experience.

In undamaged materials such as intact aluminum, steel or plexiglass, the manifestations of nonlinear response are extremely small and difficult to measure. These materials respond with *atomic nonlinearity*, or deformation at the atomic/molecular scale. Their nonlinear behavior is well understood and well described by classical nonlinear acoustical perturbation theory (e.g. Hamilton 1986). In the same materials, when damaged, the nonlinear response and the manifestations of nonlinearity are very large and easy to measure (Byers et al. 1999; Nazarov & Sutin 1997; Naugolnykh & Ostrovsky 1998; Sutin & Nazarov 1995; Van Den Abeele et al. 1999). The large nonlinear response arises from the complex compliance of local or volumetric cracks that are mesoscale (10^{-9}m) and larger, entirely dominating the relatively small atomic nonlinearity. Indeed, the nonlinear response is far more complicated than the cracks themselves, being also related to fluids in cracks and adsorbed fluids on crack walls. The full mechanism of the nonlinear response is not yet well understood. Fortunately, however, application of NWMS does not require an understanding of the mechanism of nonlinearity. From various static and dynamic experiments we do know that micro-cracked materials cannot normally be described by classical theory. When damaged, intact materials become what we call *Nonlinear Mesocopic Elastic* materials and have at least one of the following properties: they are highly nonlinear, and/or exhibit hysteresis and discrete memory in their stress-strain relation (Johnson & Guyer 1999). The theoretical description of nonlinear mesoscopic elastic materials contains terms that describe classical nonlinearity, as well as hysteresis, and discrete memory (e.g., McCall & Guyer 1994; Guyer et al. 1994; Nazarov 1995; Van Den Abeele et al. 1997; Gusev et al. 1998). Qualitatively we can say that the more damaged a material is, the larger is its nonlinear response. The quantitative relationship has yet to be demonstrated, however.

In this paper we describe the NWMS method and provide examples from three different materials. Two of the materials, plexiglass and an engine component, are intact materials that, when cracked, become nonlinear mesoscopic materials. The third material is a sandstone. Sandstone is composed of atomic material bonded together by contacts that can be soft. This rock also generally has numerous microcracks. Because of its architecture, it is nonlinear mesoscopic to begin with. When a crack is added, it becomes even more nonlinear, as will be illustrated. All these results indicate that the nonlinear response of the material when damaged is extremely large when compared to the intact material.

2 EXPERIMENT AND CONFIGURATION

Figure 1 depicts the experimental configuration in applying NWMS. The plexiglass and sandstone samples were cut in the manner shown in the figure in order to quantitatively control the cracking of the sample. In short, the cracks were induced by confining the sample center and applying tension to the region of the hole. Table 1 indicates sample dimensions and crack lengths. Experiments were conducted before and after cracking. In the experiments, two continuous waves with separate frequencies are input into the sample simultaneously using piezoelectric transducers. The first transducer generates a low frequency signal (typically 5 to 20 kHz), the second one a high frequency wave (typically 70 to 120 kHz). The waves are detected by a calibrated accelerometer at a separate location on the sample. The waveform is preamplified and collected by a 16 bit digitizer, and Fourier analyzed. To illustrate the nonlinear response, one frequency is held at a constant amplitude and the other is stepped up in amplitude from nearly zero to 10 volts input. In a sample that is intact (atomic), the output spectrum contains the two frequencies that have been affected by linear processes of wave dissipation and scattering, and by very small atomic nonlinearities. In a sample that is damaged (or nonlinear mesoscopic to begin with), harmonics and sidebands are created by the nonlinearity of the medium in addition to the linear effects. The presence of the harmonics and sidebands indicates microcracking and damage. The relationship between the drive amplitudes and the harmonics/sidebands provides clues to the type of nonlinearity of the material.

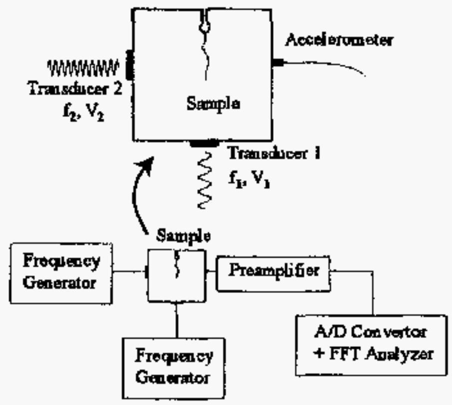

Figure 1. Sample geometry and experimental configuration for the plexiglass and sandstone samples.

3 RESULTS

3.1 Plexiglass.

In the experiment with plexiglass, the two drive frequencies applied were f_1=7 and f_2=70kHz, respectively. Drive amplitudes for f_1 were 0, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6, and 10 volts, respectively, and V_2 was held fixed at 3V (the experiment was duplicated for V_2 at 6V as well). The experiment was performed on an intact sample and on a sample with a 5cm long crack. The linear attributes of the waveforms, dissipation and wavespeed, remained

Table 1. Sample dimensions and crack sizes.

	Sample Dimensions (mm)	Hole Diameter (mm)	Crack Length (mm)
Plexiglass	110×110×6	13	50
Sandstone	90×87×18	13	20

the same in both measurements. Figure 2 illustrates the wave modulation spectra at three amplitude levels for the undamaged and damaged samples, respectively. There is some amount of harmonic and sideband energy in the intact sample. This is due primarily to nonlinearities in the associated electronics, and a small portion is due to the inherent atomic nonlinearity of the material. In contrast, the damaged sample shows considerably larger harmonics and sidebands. In order to quantify the relationships between the drive frequencies and the harmonic/modulation signals, we analyzed their dependency on the measured low frequency amplitude, and plotted them in Figure 3. It is clear from the intact plexiglass results shown in the top of figure 3 that our system noise is of order -40dB. Above this level we can rely on the observations. The bottom portion of Figure 3 illustrates the results from the cracked sample. Here we see that the second harmonic $2f_1$ increased in amplitude by at least 20 dB compared to the uncracked sample, and that it has a power law relation of two with the fundamental. This means that the second harmonic has originated by a two-fold frequency interaction between f_1 and itself. The first modulation terms (the actual sum and difference frequencies, respectively indicated by M+ and M-) have a slope of one. They originate as a result of a first order interaction between the low and the high frequency signal. Compared to the uncracked plexiglass sample, the level of the first modulation frequencies increased by 20 dB, similar to the increase of the second harmonic. The levels of the third harmonic and of the second modulation terms (M2+ and M2- at frequencies f_2+2f_1 and f_2-2f_1, respectively) are too small to be analyzed.

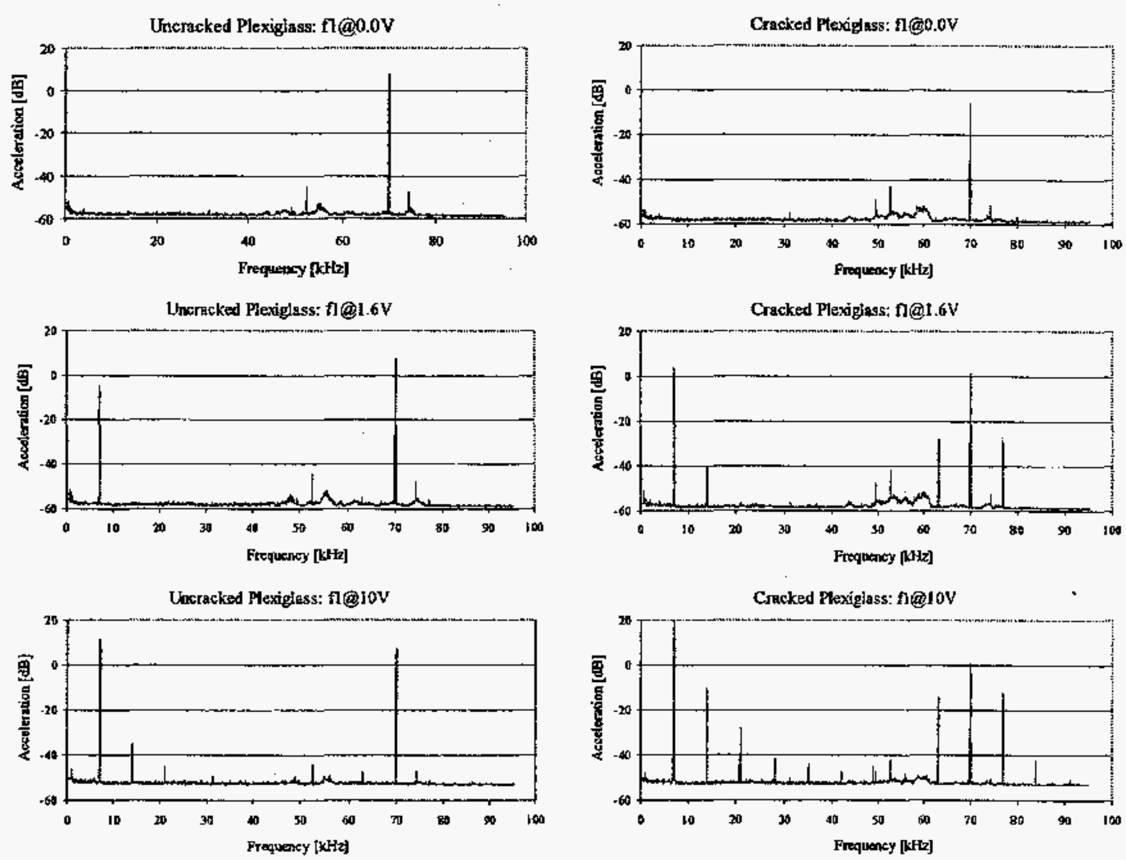

Figure 2: Wave modulation spectra (f_1=7kHz, f_2=70kHz) of intact and cracked plexiglass at 0, 1.6 and 10V drive amplitude for f_1 and constant V_2 drive.

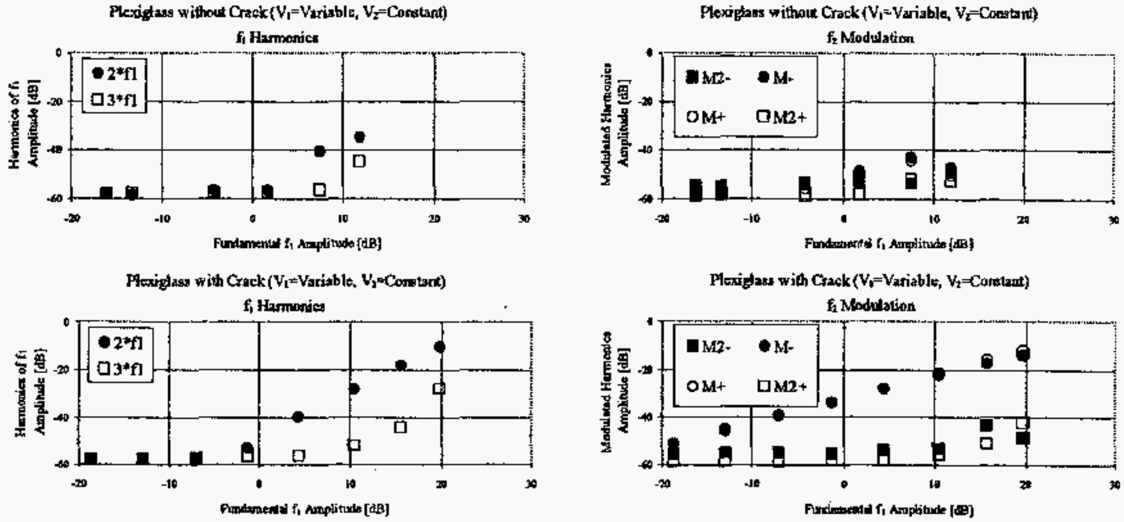

Figure 3: Analysis of the wave modulation spectra for intact and cracked plexiglass as a function of the measured fundamental f_1 amplitude. *Top*: analysis for the uncracked plexiglass. *Bottom*: analysis for the cracked sample. *Left*: Harmonics $2f_1$ and $3f_1$. *Right*: First and second modulation frequencies M+ (at f_2+f_1), M- (at f_2-f_1), M2+ (at f_2+2f_1), M2- (at f_2-2f_1).

3.2 Sandstone

We performed a similar experiment on a sandstone sample where the two modulation frequencies applied were f_1=7.9 and f_2=82.4kHz, respectively. This time, we investigated the harmonic and sideband growth as a function of the amplitude of the high frequency signal. The drive amplitudes for f_2 ranged from 0 to 10V, and V_1 was held fixed at 3V. As before, the experiment was performed on an intact sample and on a sample with a 2cm long crack. Wavespeed and dissipation remained the same in both measurements.

Sandstone is a completely different material than plexiglass. It is composed of grains bonded together by soft contacts and generally, it has numerous microcracks, which makes it nonlinear mesoscopic to begin with. The amplitude dependent spectra for the uncracked and cracked sandstone sample are illustrated in Figure 4. This figure is an interpolated contourplot with frequency on the horizontal axis, drive voltage V_2 on the vertical axis, and with a grayscale which corresponds to the measured frequency content (lighter tones correspond to higher amplitudes). This figure clearly illustrates that an inherently mesoscopic material becomes even more nonlinear when a crack is added.

To quantify the amount of damage, we analyze the dependence of the modulation harmonics on the measured high frequency amplitude. These are plotted in Figure 5. The uncracked sample shows a slight appearance of the first modulation frequencies above the noise level of -60dB. There's no evidence of measurable second order modulation. The results for the cracked sample, however, show large levels of first and second harmonics (in both sum and difference components). Again, the increase is at least of order 20dB. Further, we observe that all modulation harmonics have a power law relation of one with the fundamental f_2 amplitude.

In a complementary experiment we fixed the drive amplitude of the high frequency signal (6V) and varied the low frequency component. The analyzed results for the cracked sample are shown in Figure 6. From the harmonic data, we see a quadratic dependence for both the second and the third harmonic on the fundamental f_1 amplitude. In addition, the modulated components appear to be linear in the low frequency amplitude. The observations from both experiments combined indicate that the second as well as the third harmonic originate from a two-fold f_1 interaction and that both the first and the second modulation sidebands arise from a two-fold frequency interaction between f_1 and f_2. However, if classical perturbation theory for nonlinear wave propagation would apply, a slope of three would be predicted for the third harmonic of f_1, together with a slope of two for the second order modulation terms (M2+ and M2-) as a function of the f_1 amplitude. This discrepancy between the classical theory and these experimental results can only be explained by the existence of hysteresis and discrete memory (McCall & Guyer 1994; Guyer et al. 1994; Nazarov 1995; Van Den Abeele et al. 1997; Gusev et al. 1998). This should be no surprise however because we know that all sandstones are mesoscopic nonlinear to begin with.

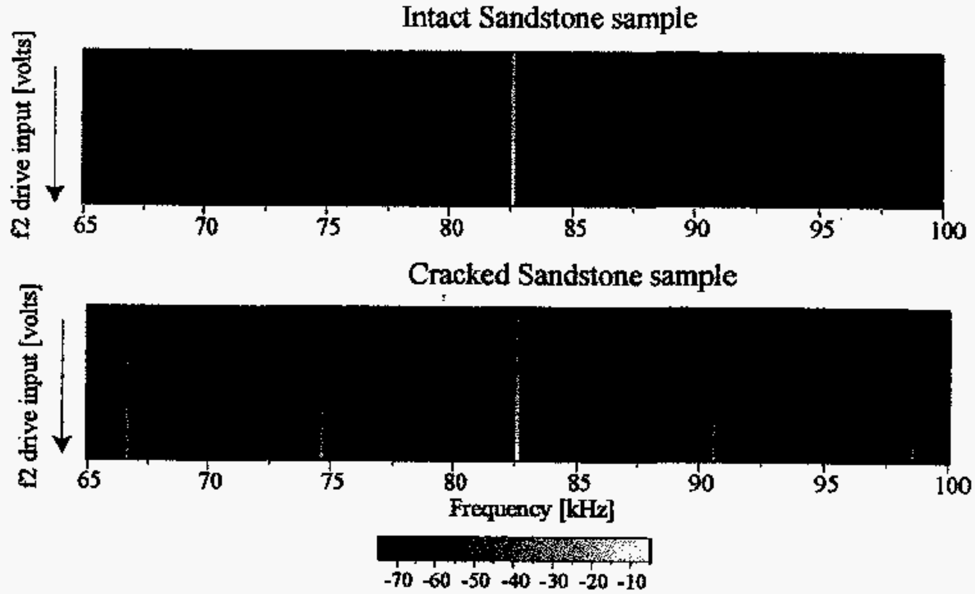

Figure 4. Interpolated contourplot of the wave modulation spectra (65-100kHz band) for uncracked and cracked sandstone in the case of a fixed f_1 drive voltage. The spectral frequency is on the horizontal axis, the f_2 drive voltage (V_2) is on the vertical axis (applied voltage increases downwards), and the grayscale corresponds to the measured frequency amplitude (lighter colors mean higher amplitudes). The existence of sidebands becomes apparent in the cracked sample.

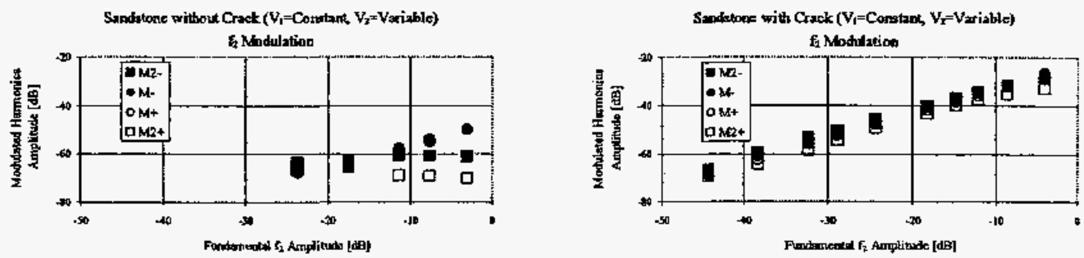

Figure 5: Analysis of the wave modulation spectra for intact and cracked sandstone as a function of the measured fundamental f_2 amplitude (applied V_1 remains constant). *Left*: analysis of the first and second modulation frequencies for the uncracked sandstone. *Right*: analysis for the cracked sample

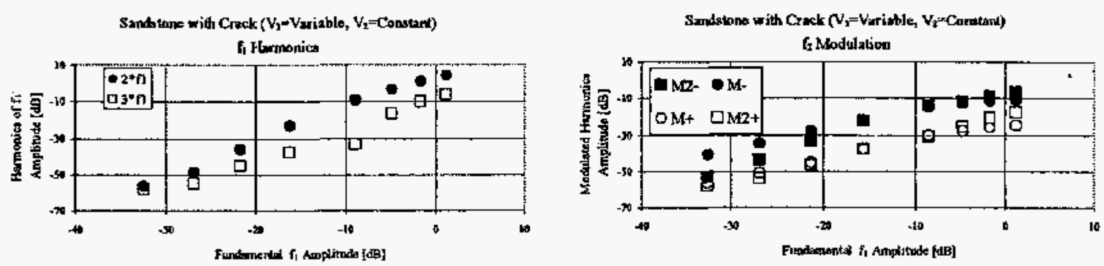

Figure 6: Analysis of the wave modulation spectra for the cracked sandstone sample as a function of the measured fundamental f_1 amplitude (applied V_2 remains constant at 6V). *Left*: analysis of the harmonics. *Right*: analysis of the first and second modulation frequencies.

3.3 Automobile engine component

Nonlinear wave modulation experiments have been carried out in materials with complex geometries as well. The tests using complex geometries included those on automobile engine connecting rods, components that are composed of a bar with open circular shapes at each end, much like an elongated number 8. We performed NWMS in two ways: 1) by studying the interaction of two monofrequency continuous wave at various drive voltages of the low frequency signal (CW-mode NWMS), and 2) by a time window analysis of the interaction between a high frequency continuous signal and the entire resonance mode spectrum of the sample which was excited by tapping the sample with an impact hammer (Impact-mode NWMS). Application of both NWMS techniques was successful at discerning an undamaged and a sample with a small crack.

In CW-mode, the two modulation frequencies applied were f_1=6.7 and f_2=127.3kHz. The drive amplitudes for f_1 were increased in seven intervals to an input level of 10V. V_2 was held fixed. Figure 7 (again in the form of an interpolated contourplot) shows the amplitude dependent spectra for the undamaged and cracked connecting rods. The figures clearly illustrate the abundance of harmonics and sidebands in the cracked sample compared to the intact one. This dramatic increase is also visible in Figure 8 where we plot the level of first and second order sum frequencies as a function of the fundamental f_1 amplitude for both the intact and the cracked sample. In the latter, we observe a slope of one for the dependence of the first sum frequency component M+, and a slope between 1 and 2 for the second order sum frequency M2+. Similar results were obtained for the first and second order difference frequencies. This lead to the interpretation that the second order modulation harmonic originates from a mixed contribution of classical and hysteretic nonlinear phenomena. The cracked sample definitely displays mesoscopic nonlinearity.

In the Impact-mode, we tapped the samples with an impact hammer while a high frequency signal was simultaneously applied to the sample. Due to the impact, all resonance modes are excited. Their spectrum is limited in the frequency band to about 20 kHz because of the attenuation of the material. In addition, the low frequency content generated by the impact only last for a limited time, and is attenuated with a characteristic decay time. In order to analyze the nonlinear (or amplitude dependent) behavior of the samples, we applied a moving time-window analysis to the measured signal by dividing the time record in 6 intervals. For each of these intervals a spectral analysis was performed. The most interesting parts of the modulation spectra are shown in Figure 9. Even though energy is abundantly present in the low frequency band, there is no

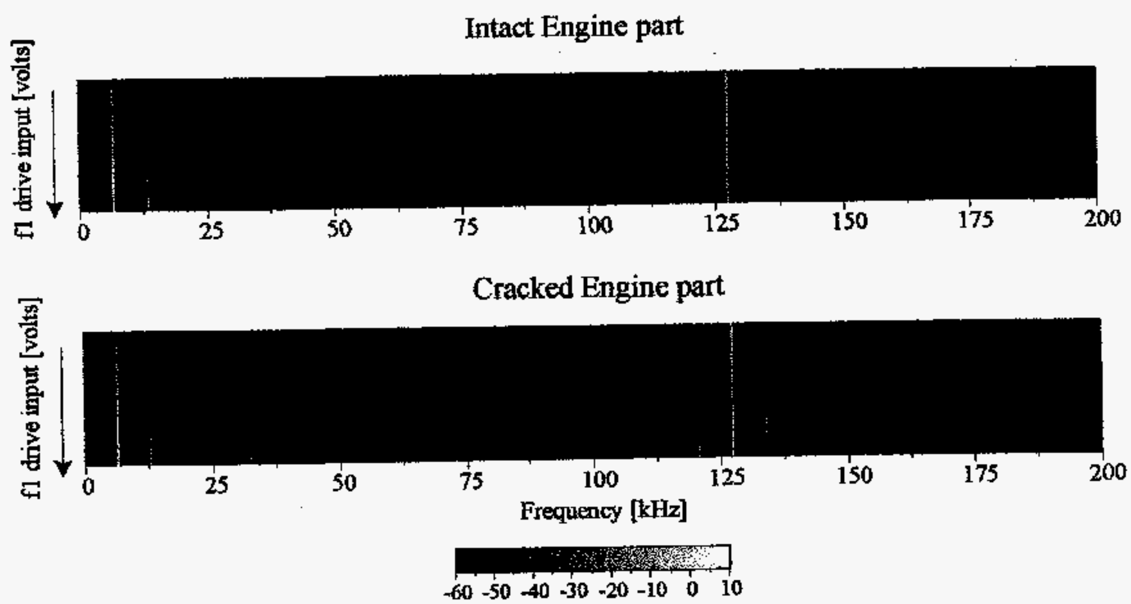

Figure 7. Interpolated contourplot of the wave modulation spectra for an undamaged and a cracked rocker arm in the case of fixed f_2 drive voltage. The spectral frequency is on the horizontal axis, the f_1 drive voltage (V_1) is on the vertical axis (applied voltage increases downwards), and the grayscale corresponds to the measured frequency amplitude (lighter colors mean higher amplitudes). The existence of harmonics and sidebands becomes apparent in the cracked sample.

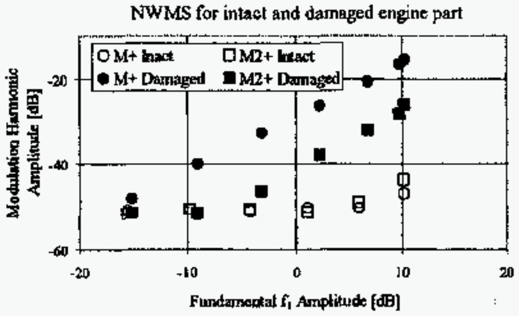

Figure 8: Analysis of the wave modulation spectra for an intact and a cracked engine part in CW-mode. Only the first and second sum frequencies are shown. The difference frequencies show similar behavior.

interaction with the high frequency component for the intact sample. On the other hand, the damaged sample shows large levels of energy in the sidebands, even in the last time-window when the impact energy has nearly disappeared.

The analysis of the wave modulation spectra in the Impact-mode can be performed as follows: 1) define the frequency bands of interest at low frequency (containing all the resonance modes) and around the high frequency input signal (including all sideband modulations); 2) integrate both spectral bands, yielding the values I_1 and I_2 for the low and the high frequency, respectively; 3) subtract the integral of the f_2 component from I_2, and 4) plot this value against I_1. The result of this procedure is shown in Figure 10. For the intact unit, there's almost no variation. For the damaged unit, a linear increase is observed. The proportionality coefficient of this relationship may be used as a damage indicator in quality control, e.g. integrated in a production line.

4 DISCUSSION AND CONCLUSIONS

The results presented here indicate that the nonlinear response of a material when damaged is extremely large when compared to an intact material. Therefore, acoustic diagnostic methods that primarily look for nonlinear phenomena such as wave distortion by creation of harmonics, multiplication of waves of different frequencies, nonlinear attenuation, and amplitude dependent resonance frequency shift, have a strong potential in damage detection. In undamaged materials, the nonlinear phenomena are very weak. In damaged materials, they are remarkably large. Because of the

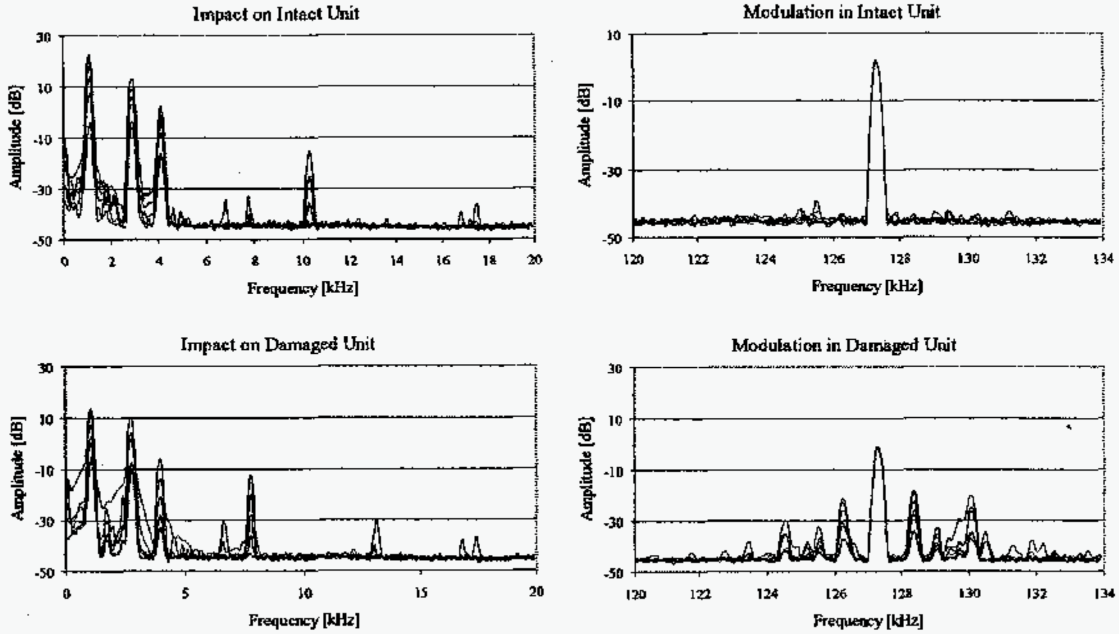

Figure 9: Low and high frequency spectra in NWMS Impact-mode (6 levels) for an intact and a cracked engine part.

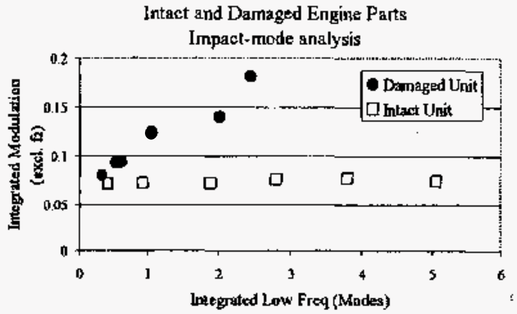

Figure 10: Integration analysis of the wave modulation spectra for an intact and a cracked engine part in Impact-mode.

complex (i.e. nonlinear and hysteretic) compliance of cracks and flaws, the sensitivity of nonlinear methods to the detection of damage features is far greater than any linear acoustical methods.

The method outlined in this paper focussed on the nonlinear interaction of low and high frequency signals. The method is fast and efficient, and proved to be very effective in discerning an undamaged and a sample with a small crack. It can be applied to any type of geometry.

There are potentially a huge number of applications of enormous economic and safety impact that will evolve from nonlinear studies such as this one. It is not an understatement to suggest that within 10 years nonlinear methods may be routinely used in applications as diverse as monitoring reactor containment walls for damage, inspecting aircraft and spacecraft, observing fatigue damage in buildings, bridges, tunnels, gas and oil pipe lines, etc.

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REFERENCES

Byers, L.W., J.A. TenCate, G. Guthrie, W. Carrie, and P.A. Johnson, Application of Single-Mode Nonlinear Resonance Ultrasound Spectroscopy to Detect Damage in Concrete, J. Cement and Concrete, in review, 1999.

Gusev, V.E., W. Lauriks, and J. Thoen, Dispersion of nonlinearity, nonlinear dispersion, and absorption of sound in micro-inhomogeneous materials, *J. Acoust. Soc. Am. 103(5)*, 3216-3226, 1998.

Guyer, R.A., K.R. McCall, and G.N. Boitnott, Hysteresis, discrete memory and nonlinear wave propagation in rock: a new paradigm, *Phys. Rev. Lett. 74*, 3491-3494, 1994.

Hamilton, M. F., Fundamentals and applications of nonlinear acoustics, in *Nonlinear wave propagation in Mechanics - AMD-77*, The American Society of Mechanical Engineers, New York, 1986.

Johnson, P.A. and R.A. Guyer, The astonishing case of mesoscopic elastic Nonlinearity, Physics Today, in press 1999.

Johnson, P.A., B. Zinszner, and P.N.J. Rasolofosaon, Resonance and nonlinear elastic phenomena in rock, J. Geophys. Res, 11553-11564, 1996.

McCall, K.R., and R.A. Guyer, Equation of State and wave propagation in hysteretic nonlinear elastic materials, *J. Geoph. Res. 99*, 23887-23897, 1994.

Naugolnykh. K. and L. Ostrovsky, Nonlinear Wave Processes in Acoustics, *Cambridge Texts in Applied Mathematematics*, Cambridge University Press, 1998.

Nazarov, V.E., Propagation of a unipolar impulse in a medium with hysteretic nonlinearity, *preprint IAP n.383, N. Novgorod, 1995.*

Nazarov V.E. and A.M. Sutin. Nonlinear elastic constants of solids with cracks. J. Acoust. Soc. Am. 102 (6), 3349-3354, 1997.

Sutin, A.M. and V.E. Nazarov, Nonlinear acoustic methods of crack diagnostics, Radiophysics & Quantum Electronics, 38(3-4):109-120, 1995.

Van Den Abeele K., P.A. Johnson, R.A. Guyer and K.R. McCall, On the quasi-analytic treatment of hysteretic nonlinear response in elastic wave propagation, *J. Acoust. Soc. Am.* 101(4), 1885-1898, 1997.

Van Den Abeele K., Damage detection in slate using Single Mode Nonlinear Acoustic Spectroscopy, *submitted to J. Appl. Phys., 1999.*

Van Den Abeele K. and J.A. TenCate, Acoustic characterization of nonlinear and hysteretic geomaterials: Single Mode Nonlinear Resonant Ultrasound Spectroscopy (SIMONRUS), submitted to J. Geoph. Res., 1999.

Van Den Abeele K., J. Carmeliet, J.A. TenCate, and P.A. Johnson, Single Mode Nonlinear Resonance Acoustic Spectroscopy for damage detection in quasi brittle materials, this issue, 1999.