Nonlinear Elastic Wave Spectroscopy (NEWS): a Diagnostic Tool to detect Microdamage with high potential for Nondestructive Testing

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Abstract

The macroscopic signatures of microdamage resulting from the nonlinearity and non-uniqueness of the stress-strain relation at the microscopic level include amplitude dependent modulus reduction, nonlinear attenuation, generation of harmonics and intermodulation frequencies, phase modulation, slow dynamics, etc. Nonlinear Elastic Wave Spectroscopy (NEWS) comprises a relatively new class of innovative non-destructive techniques that exploit these signatures for diagnostic purposes. Several exemplary laboratory studies are selected to illustrate the high sensitivity of NEWS in comparison with traditional linear techniques for the detection of incipient damage in the form of microcracks or delaminations, weakening of adhesive bonds, thermal and chemical damage, and for the monitoring of microstructural evolutions. In addition to being a diagnostic technique, macroscopically observed signatures of nonlinearity can be introduced in innovative approaches for new and sensitive imaging techniques. As an example, the combination of classical Time Reversed Acoustics and nonlinear response brings about a significant enhancement of imaging localized areas of microdamage, and is one of the only techniques known today to discriminate between a linear and a nonlinear scatterer. The concept of NonLinear Time Reversed Acoustics (NLTRA) is discussed both from a numerical and an experimental point of view.

Introduction

Recent advances in modern material technology require the development of non-destructive evaluation (NDE) techniques that allow the quantification and localization of microstructural damage in a wide variety of materials during their manufacture and life cycle. The monitoring of these materials, including alloys and composites, ensures both their quality and durability. Traditional NDT techniques such as high quality linear acoustic, electromagnetic and visual inspection methods are often not sufficiently sensitive to the presence and development of domains of incipient and progressive damage. Indeed, the subtle changes in the material’s micromechanical behavior during the early stages of damage does not provide the necessary contrast in the measurements for such techniques to be able to pinpoint the (existence of the) damage. During the last decade several researchers from all over the world have developed innovative techniques that explicitly interrogate the material’s micromechanical behavior and its effect on wave propagation by investigating the amplitude dependence of certain macroscopically observable properties [1-17]. Such techniques are termed Nonlinear Elastic Wave Spectroscopy (NEWS) techniques. The basis of all NEWS techniques is to measure and analyze macroscopic signatures resulting from a local violation of the linear stress-strain relation at the microscale. This violation of Hooke’s constitutive law can be attributed to a nonlinear dependence of stress on strain, or to a non-uniqueness of the relation depending on the stress or strain rate [1-3,18]. Figure 1 illustrates this non-linear behavior for a sandstone sample under uniaxial stress during a quasi-static experiment. It is commonly accepted that the compliant structure of the material (solid grains in a soft matrix, with internal contacts) is responsible for this comportment. Even though the nonlinearity in Figure 1 reflects the behavior at relatively large strain values, it is believed that the micromechanical changes in the stress-strain relation are also drastically influencing the dynamic response of materials subjected to much lower values of deformation, i.e. in the acoustic regime.

Several NEWS techniques have been developed to probe for the existence of damage induced nonlinearity (e.g., delaminations, microcracks or weak adhesive bonds) by investigating the generation of harmonics and intermodulation of frequency components, the amplitude dependent shift in resonance frequencies, and the nonlinear contribution to attenuation properties. The concept of NEWS-based methods is that the internal damage can be measured directly with the instantaneous detection of an increase in the nonlinearity parameters. The direct connection between nonlinearity and microdamage in metals and composites is established without doubt in several

Figure 1: Example of nonlinear behavior in rocks: evidence obtained in a quasi-static uniaxial compression experiment on Serena Sandstone showing a nonlinear and non-unique stress-strain relation, including end-point-memory effects.
preliminary experimental case-studies. Among others, we mention damage probes such as Nonlinear Wave Propagation [4-5], Nonlinear Wave Modulation Spectroscopy [6-8], SIngle MOde Nonlinear Resonance Acoustic Spectroscopy [9-11], Nonlinear Reverberation Analysis [12-13], Slow Dynamics [14-15], Phase Modulation [16], Wave Demodulation and Self-Action [17], etc. Tests performed on a wide variety of materials subjected to different microdamage mechanisms of mechanical, chemical and thermal origin, have shown that the sensitivity of such nonlinear methods to the detection of microscale features is far greater than that obtained with linear acoustical methods [19-21].

The following section contains three selected examples of the use of NEWS techniques in Nondestructive Testing of solid materials.

**NEWS examples**

**Nonlinear Reverberation Spectroscopy**

The first example concerns the application of Nonlinear Reverberation Spectroscopy (NRS [12-13]) to the evaluation of thermal damage in Carbon Fiber Reinforced Plastics (CFRP). In NRS, a sample is excited at a constant amplitude and a constant frequency (chosen in the neighborhood of one of the resonance frequencies of the sample) for a certain period of time. In practice this can be done for instance in a non-contact mode by using a loudspeaker. After a number of cycles, sufficient for the sample to reach its steady state response, the continuous wave (CW) excitation is stopped at t=t₀, and the reverberation response of the sample is measured from t₀ to t₁, and stored. The response measurement can also be performed without contact, using a laser vibrometer. The reverberation signal is typically a decaying time signal, with large amplitudes near t₀, and smaller amplitudes near t₁. Appropriate synchronization allows averaging of the signal and a feedback loop can be used to increase the dynamic range as function of the measurement time. The decay signal is then analyzed using a successive fitting of an exponentially decaying sine function, with amplitude, decay-time, frequency, and phase as free parameters, to small time windows (approximately 20 cycles). This allows the creation of a parametric plot of the true resonance frequency as function of the amplitude, thereby giving us a nonlinear signature. If the material is linear the frequency in different windows of the reverberation signal remains constant. If the material is nonlinear, the frequency in the reverberation signal gradually increases with time, and thus with decreasing amplitude. Figure 2 clearly shows this behavior for three samples of CFRP: a reference sample, a sample treated at 250°C for 30’, and a sample treated at 300°C for 45’. The linear decrease of the frequency with increasing strain is exactly what can be expected from a hysteretic material model. The slope of this relation can be used as a nonlinearity signature. It is important to note that the slope is independent of the excitation frequency as long as it is not too far from the natural frequency. Figure 3 illustrates the slope evolution at different temperatures and exposure times. A comparison with traditional A-scans shows that the nonlinearity indeed correlates well with the observations of increased delaminations.

![Figure 2: Resonance frequency analysis as a result of the Nonlinear Reverberation spectroscopy technique applied to thermally damaged CFRP samples (reference, 250°C-30”, and 300°C-45”), normalized to the linear (low amplitude) frequency value in each case.](image1)

![Figure 3: Evolution of the NRS signature in CFRP samples as function of temperature (Ref-240-250-260-270-300°C) and exposure time (15-30-45-60’), and its comparison with traditional A-scans.](image2)
A similar study has been performed for CFRP samples subjected to 3-point fatigue bending. In Figure 4 we see that the sensitivity of the nonlinear signature is much larger than the sensitivity of a linear material property such as the attenuation.

**Nonlinear Wave Modulation Spectroscopy**

In the second example we apply the Nonlinear Wave Modulation Spectroscopy (NWMS [6-8]) technique to an intact and a damaged automobile engine connecting rod, a steel component that is composed of a bar with open circular shapes at each end, much like an elongated number 8. In NWMS, we study the interaction of a high and a low frequency CW signal at increasing drive voltages. Here, the two modulation frequencies applied were $f_1 = 6.7\,\text{kHz}$ and $f_2 = 127.3\,\text{kHz}$, and the drive amplitudes ($V_1$) for $f_1$, before amplification, were increased in seven intervals to an input level of $10\,\text{V}$. The voltage of $f_2$ was held fixed. If the material is intact, we expect no interaction of both frequencies (some electronically generated harmonics of $f_1$ may appear). If the material is damaged, the local nonlinearities in the microstructure will create intermodulation frequency components in the spectrum; the low frequency component activates the nonlinearity and modulates the amplitude of the high frequency probe. Figure 5 (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 as a function of the voltage $V_1$. This striking increase is also visible in Figure 6 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 case, we observe a slope of one for the dependence of the first sum-frequency component at $f_1 + f_2$, and a slope between 1 and 2 for the second order sum frequency at $2f_1 + f_2$. Similar results were obtained for the first and second order difference-frequencies. This leads to the interpretation that the second order modulation harmonic originates from a mixed contribution of classical (reversible) and hysteretic nonlinear phenomena. The cracked sample definitely displays the signs of a mesoscopic nonlinearity.

**Nonlinear Wave Propagation Spectroscopy**

The third and last example is an illustration of the Nonlinear Wave Propagation Spectroscopy (NWPS [4-5]) technique. In NWPS, one simply analyses the level of harmonics generated by a fixed frequency continuous wave propagating through a sample as function of the fundamental response amplitude. Here we have chosen an application which is not particularly related to the evaluation of damage. Rather, we have applied NWPS to evaluate the phases of microstructural changes in young concrete during its early hydration process [22-24]. In order to do this, we have developed an integrated system combining passive and active sound interrogation. The system is based on acoustic emission (AE) monitoring, on one side, and on the evaluation of the pulse velocity and the generation of harmonics in the propagation of longitudinal (P) and
transversal (S) waves, on the other side. Therefore, we instrumented a lucite sample holder for freshly poured concrete with temperature sensors, AE sensors and two sets of P and S wave transducers. The nonlinear coefficients are obtained by evaluating the harmonic component $A_2$ at the double frequency in a burst of a 100 kHz signal (sequentially for P and S waves), as function of the fundamental frequency response amplitude $A_1$. The proportionality coefficient in the square law relation between $A_2$ and $A_1$ gives the value of the nonlinear signature. Figure 7 illustrates the evolution of the measured values as function of time during the first three days.

Looking at the temperature profile, a relatively silent start is followed by a crucial temperature increase, reflecting the internal accumulation of heat due to chemical reactions [22-23]. The first chemical reaction starts really early in the process, about 2 hours after the preparation of the concrete, and the increase lasts for about 12 hours. It is during this period that most clustering between the different particles is established, first between the smallest and later between the largest particles. After reaching the temperature peak, a diffusive process causes the hydration products to fill the small pores in the matrix. Finally, the temperature decreases gradually back to room temperature during the subsequent mechanical setting phase. If we now focus to the nonlinear signatures, we note that, in the “fluid” phase, the attenuation is too large and the transmission intensity too small to generate measurable nonlinear effects. However, as the chemical activity in the concrete develops and the percolation threshold is reached (just before the peak in temperature), we observe a significant increase of the S-wave nonlinearity. We hypothesize that this increase reflects the micromechanical friction which is generated through the partial connection of the particles. As soon as the connections become better and better, the transverse nonlinearity decreases, together with the temperature. The development of the longitudinal nonlinearity is delayed with respect to the shear nonlinearity, and manifests itself primarily during the late chemical activity (the capillary pore filling stage) and in the early mechanical creep (creation of shrinkage microcracks which can be activated by the pressure waves). In the subsequent phase we observe again a renewed contribution of the shear nonlinearity. This time we attribute the raise to the increased mechanical shrinkage which is changing the stress state inside the concrete sample significantly and is creating microcracks with large enough openings to be susceptible to nonlinear shearing. However, once the cracks are too wide open and under too high stresses, the nonlinearity cannot be activated anymore by the dynamic waves and we expect a subsequent drop at later times. In conclusion, we conjecture that the origin of the observed nonlinearity is connected to the micromechanical changes in the composition, both due to chemical reactions (mostly shear nonlinearity) and to progressive mechanical setting of the sample (longitudinal and shear).

The above three examples illustrate the power and sensitivity of NEWS techniques to diagnose damage and monitor microstructural changes. In the following section, we reflect on the use of NEWS techniques to localize damage.

Figure 7: Evolution of the temperature, cumulative AE-events, P and S wave pulse velocity and P and S wave nonlinear coefficients during the early concrete hydration process.

Localization of Microdamage using NEWS
Following the laboratory studies using NEWS techniques we underline two important principles: 1) the macroscopically observed nonlinear signatures originate from zones with microdamage and micromechanical nonlinear stress-strain relations; and 2) the nonlinear signatures are most efficiently generated at locations where the strain within the sample is largest. These two principles can be used as the basis for
new microdamage visualization techniques [25-28]. In the following, we sketch several possible procedures. We distinguish between a global and a local approach.

Global Interrogation approach

As a global approach, we suggest a NEWS methodology that interrogates the sample successively at more than one resonance mode [26]. To study the nonlinearity at a specific mode, one can use the NRS technique in example 1 [12-13], or the frequency analogue of NRS which is known as SIMONRUS [9-11]. By interpreting the extent of the resonance frequency shift and/or the harmonic generation at several resonance modes in relation to the corresponding stress field of the resonance modes, one can proceed to a localization of the source of the nonlinearity. To do this it suffices to weight the nonlinear signature at each mode by its characteristic strain power distribution. This methodology is called Multimode Nonlinear Resonance Ultrasound Spectroscopy, or short MuMoNRUS.

As an example, we assume a simple one-dimensional system (0 \leq x \leq L) which we drive longitudinally at one end. If the system contains a local source of nonlinearity (microdamage), we can examine the nonlinear resonance response of the object near its first N resonance frequencies \( f_k = \frac{k}{2L} c \), with \( L \) the length of the sample and \( c \) its (longitudinal) velocity. Suppose that \( S_k \) is the proportionality coefficient in the relation between the resonance frequency shift and the strain at mode \( k \) (i.e., when hysteresis prevails, \( \Delta f_k / f_k = S_k \epsilon \), with \( \epsilon \) the maximum strain amplitude in the strain distribution of mode \( k \)) than the weighted MuMoNRUS distribution can be expressed as:

\[
W(x) = \sum_{k=1}^{N} S_k \left[ \sin \left( k \frac{\pi}{L} x \right) \right]^2
\]

The maximum of the function \( W(x) \) betrays the location of the microdamage. A numerical example, following a theoretical model for the calculation of \( S_k \) presented in reference X, is given in Figure 8 for a hysteretic zone of 5 mm in a 250 mm long bar, located at 80 mm from the edge. The MuMonRUS function \( W(x) \) is shown for the first 5 modes and the first 15 modes. The procedure is extremely efficient in the determination of the defect position, except for the fact that due to the symmetry of the modes with respect to the centre of the specimen a defect is also detected at its mirror position. This symmetry can be broken only by changing the experimental configuration, e.g. by keeping one boundary of the specimen fixed.

This localization method can be easily extended to more dimensions taking into account the nonlinear properties at various resonance modes (including torsional and bending modes), and weighing the contribution with the corresponding strain field.

Local Interrogation approach

As a more local approach to the localization of microdamage, we mention here the recent efforts in the development of a nonlinear version of the well-known Time Reversed Acoustics (TRA) technique [27-28].

The basic premise of TRA is the following [29-31]: If the wavefield can be known as a function of time on some boundary surrounding a given region, then it can also be found at every point inside that region at previous times by using the wave equation with time running backwards. In other words, the result of a time-reversal process is that the waves recorded on the boundary are focused back in space and time on the acoustic sources, or on the scattering targets inside the region which were acting as sources. One of the benefits of TRA is that it enables us to locate strong scatterers (voids and interfaces with high impedance contrast) which are hidden inside a region. For more delicate scatterers such as zones of microdamage, weakened bonds or tiny defects, the sensitivity of classical TRA has found to be quite low. The main reason for this is that the principle used in TRA applications is based on linear time reversal, and relies on the wave propagation changes due to the linear scattering at inhomogeneities in the material, i.e., reflections, refractions, mode conversions. Our experience in NEWS techniques have demonstrated that microdamage is first of all a process of nonlinear scattering giving rise to the creation of higher harmonics, rather than to “linear” scattering effects. So, from our point of view, the classical TRA procedure should be modified in such a way that the main signal treatment is concentrated on the nonlinear components of the signals. One of the alternatives to classical TRA consists in selecting only the nonlinear/harmonic energy contained in the response signals and returning merely this part back into the medium by the time reverse mirror. Doing so, the time reversed signal will
focus on the microdamaged area, which is the zone where the harmonics were created, while “linear scatterers” will not show up at all.

The difference in classical and Nonlinear TRA is illustrated in Figure 9 which shows the results of a numerical simulation (based on a 2D extension of the multiscale method in [32]). We consider a 2D object of 200 (L) by 50 mm (B), with an expanding source located at (L/4,B/2), and a 10 by 10 mm zone of microdamage in the center. The ‘defect’ is modeled by a zone with a nonlinear hysteretic stress-strain behavior. The source is a sine wave of 5 cycles at 250 kHz, with a Gaussian envelope. If all signals at the boundaries of the object are received, time reversed (what comes out last goes in first) and sent back into the medium, the energy focuses back to the source. This is illustrated in Figure 9b where the distribution of the maximum stress values during the entire time signal at each position in the object after the TRA reemission is given. Now, if we filter the received signals first, retaining only the frequency content above 400 kHz, and send back this information in time reversed manner, we observe that all energy indeed focuses on damage zone which is the source of the harmonics (Figure 9c).

An alternative filtering procedure for the use in the NL-TRA methodology is based on the fact that the phase inversion of a pulsed excitation signal (180° phase shift) will lead to the exact phase inverted response signal within a linear medium. However, this is not the case in a nonlinear (or microdamaged) material due to the generation of harmonics. We can take advantage of this observation by adding the responses from two phase-inverted pulses (positive and negative) and sending back the sum at the receivers. We call this operation ‘phase-coded pulse-sequence (PC-PS) filtering’. The sum makes sure that all information on the linear scatterers is filtered out of the signal before time reversing it. Doing so, only the relevant information on the local nonlinearities is reversed and sent back into the material. Again, the filtered energy will focus on its sources, i.e. the microdamaged zone. Other filtering procedures may be based on the sum- or difference-frequency components \((f_2 \pm f_1)\) generated as a result of an excitation of a sample at two fundamental frequencies \(f_1\) and \(f_2\).

To verify the Nonlinear TRA methodology using PC-PS filtering, we have performed an experiment on PMMA glass (used for cockpit windows). The sample, a parallelepiped, contains two laser induced cracks in the center. We excited the sample successively using a pulsed signal (center frequency 140 kHz) with 0 and 180° phase shifts, and we recorded the response signals at a fixed location on the surface. The added response signal was then sent in time reversed mode back from the receiver position (1 channel reversal) and a laser vibrometer was used to measure the signals along a line at the surface across the crack location. Finally, using standard ultrasonic tomography, the signals were used for imaging a 2D section of the parallelepiped in the direction of the laser scan. Figure 10 shows the repartition of energy at a certain time in the reconstruction. One clearly observes a focal point located at a distance of less than half a wavelength from the center of the cracks. The result is not perfect, but considering it is performed using a one channel reversal and limited information for the reconstruction algorithm, it is encouraging. A more complete experiment on PMMA is currently under treatment.

Figure 9: Maximum amplitude plot of the linear and nonlinear TRA response of a 2D object containing a microdamaged zone in the center of the sample

Figure 10: Experimental result of the retrofocalisation on a damaged area in PMMA glass using Phase Coded Pulse Sequence filtering.
signal, point by point, to determine the extent of the damage at the surface. We finish this contribution by giving three examples illustrating several variations on this methodology.

In the first example, we consider a numerical investigation of the distribution of harmonics in the point-by-point retrofocalisation of energy for a 3D sample (200 by 140 by 2 mm) with a surface defect (see [27] for an experimental example). The surface defect, located at (150,70,0), is modeled by a zone with a nonlinear stress-strain behavior. A fixed source, located at the same surface as the defect (50,70,0), is sending out a pulsed signal which is received at a point (x,y,0), again located at the same surface. This signal is time reversed and sent back from the original source without filtering (1 channel classical time reversal). The newly received signal at point (x,y,0), which is highly focused in time and space, is then filtered using a high pass filter and the amplitude of the remaining signal at the focus in time is recorded. Figure 11 shows the evolution of the local harmonic content as function of the position in the direction of the source-defect and in the orthogonal direction. The localization of the defect is obvious.

A second variation on the theme is to investigate, point-by-point, the amplitude change of the time reversed signal due to a superimposed low frequency vibration of the sample [8]. We tested this idea on a wing panel near a rivet connecting an 2 mm aluminum sheet to a stringer. The wing panel was fatigued due to tension loading, and a tiny crack could be observed starting from the rivet, orthogonal to the stringer. The low frequency vibration is tuned to the first flexural mode of the wing panel (60 Hz), and is supposed to activate the crack. A transducer supplies a 1 Mhz signal, and the response is recorded by a laser vibrometer (without low frequency vibration present). The signal is then returned to the transducer and time reversed (single channel reversal). Using appropriate synchronisation it is possible to record the time reversed signal at different phases during the low frequency vibration while performing averaging. Figure 12a illustrates a typical variation in the amplitude of the TRA signal during a 60 Hz cycle at a single position in space. The amplitude modulation obtained point-by-point over a line scan crossing the crack is illustrated in Figure 12b. Again, we see a clear indication of the crack position.

The last example is related to the previous one, but uses two high frequency signals to excite the medium, and analyses the intermodulation of the retrofocalised signals [28]. First a 1MHz signal (f_1) is produced at source S_1. The response is recorded at a fixed location using the laser vibrometer. Then a 200kHz signal (f_2) is sent from source S_2. Again the laser vibrometer records the signal at the fixed position. Both recorded signals are then time reversed and reemitted from their corresponding original transducers at exactly the same time (two times a one channel TRA, but with appropriate synchronisation). The intermodulation at the focus in time is then analysed in terms of the sum- and difference-components (A(f_1-f_2) and A(f_1+f_2)) in the spectrum. Both nonlinearity signatures are visualized in Figure 13 as function of the distance to the crack for a line scan crossing...
the flaw. At the position of the crack, the intermodulation signature is evidently much larger than elsewhere.

Figure 13: Results of TRA, extended with frequency intermodulation analysis, for a cracked wing panel: Point-by-point assessment of the high frequency intermodulation signatures in the retrofocalized TRA signals as function of the distance to the crack. The frequencies applied are 200kHz and 1MHz. The intermodulation signature corresponds to the sum- and difference-frequency components at the retrofocalisation.

Conclusion

Recent work has proven that Nonlinear Elastic Wave Spectroscopy techniques are superior to linear acoustic techniques in diagnosing early stage damage processes in various materials. The same methods can also be used for monitoring the evolution in microstructural properties of hardening processes. One of the current challenges is to exploit and extend the successful results of NEWS techniques to defect localization/imaging. This can be achieved by multiple mode analysis or by adapting the Time Reversed Acoustics methodology for nonlinear wave processes. We believe that the combination of TRA and NEWS will enhance greatly the diagnostic capabilities of both TRA and NEWS techniques at many scales.

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