Spectral analysis and damage evolution in concrete structures with ultrasonic technique

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ABSTRACT: The non-linear behavior of both virgin and damaged concrete samples is experimentally investigated by means of ultrasonic tests. Recent theoretical models, indeed, have pointed out that mono-frequency ultrasonic excitations bring to light such phenomena as harmonic generation and sidebands production, which are essentially due to the material non-linearity. The estimation of the harmonic components parameters (amplitudes and phases) is achieved through a signal processing technique based on MUltiple SIgnal Classification (MUSIC) system, which reveals to be optimal for the specific signal model here considered. The experiments described in this paper show that the material non-linear features increase with increasing level of internal deterioration, thus suggesting the possibility to use the ultrasonic signal analysis in the frequency domain as a valuable tool for damage assessment.

1 INTRODUCTION

Standard methods for detecting defects within a concrete structure generally involve the use of drilled core samples. In the case of buildings and monuments of historical interest, it is frequently impossible to extract even small samples. Hence, the need for non-destructive methods in the carrying out of investigations, as for example ultrasonic techniques (UT).

Recently, UT have been widely used in the evaluation of crack growth in concrete to deduce its quality and extent of microcracking. Crack detection is usually carried out by measuring pulse velocity, or resorting to impact echo methods and others (Popovic 1994).

In the present paper a novel approach based on spectral signal-processing and analysis is discussed: it allows the monitoring of the crack growth and damage evolution within concrete structures in term of non-linear response to the application of ultrasonic waves, revealing to be fairly sensitive (Van Den Abeele et al. 2000a-b, Bentahar et al. 2006, Bocca & Rosa 1993, Bocca & Nano 1995, Daponte et al. 1995, Daponte et al. 1990).

An experimental program is planned to evaluate the performances offered by this procedure in damage assessment of granular materials, such as concrete or rocks. Laboratory tests have been conducted on ordinary concrete specimens in order to simulate a possible deterioration process affecting a real structures and consequently investigate its damage level. The final aim of this preliminary study is to develop an effective non-destructive procedure suitable to be used on-site.

The paper is organized as follows: first, the theoretical background concerning the non-linear behavior of concrete is presented; subsequently, the experimental research conducted at the Non-Destructive Testing Laboratory of Politecnico di Torino is described, with detailed reference to the materials tested, the equipment used and the procedure followed; finally, the experimental results are reported and discussed, in terms of repeatability of measurements, signal processing methods and applicability to damage assessment.

2 THEORETICAL FOUNDATIONS

Non-linearity in the elastic behavior of a material is known to be deeply dependent on the level of microcracking and damage affecting the material itself (Pugno & Surace 2000). Indeed, even in such materials as concrete or rocks, that are intrinsically non-linear due to their grain structure, the presence of damage at micro- or meso-scopic level is responsible for a dramatic increase of non-linear features. It follows that the detection of non-linear signatures could be assumed as an indicator of the state of damage.

In particular, it has been observed that material non-linearity causes distortions in the propagation of elastic waves, creating accompanying harmonics,

multiplication of waves at different frequencies, and under resonance conditions, changes in resonant frequencies as a function of the driving amplitude.
Hence the increasing importance that Non-linear Elastic Waves Spectroscopy (NEWS) techniques are assuming in diagnostics.

As a first approach, non-linearity can be theoretically modeled by expressing the elastic moduli in a power series of the strain, and considering terms of first or even second order, for highly non-linear materials. Such a power series approach is generally referred to as "classical non-linearity". Though very useful in many cases, however, this theory does not fully explain the behavior of most highly non-linear materials, that exhibit more complicated phenomena in their stress-strain relation, such as hysteresis and discrete memory (Bentahar et al. 2006). Consequently, a theoretical model suitable to describe these materials should contain terms accounting for both classical non-linearity and hysteretic behavior, as well as discrete memory. Accordingly, the one-dimensional constitutive relation between stress and strain to be used in simulation of the dynamic behavior of solids can be expressed as follows:

$$\sigma = \int k(\varepsilon, \varepsilon')\,d\varepsilon \qquad (1)$$

$k(\varepsilon,\varepsilon')$ being the non linear and hysteretic modulus given by:

$$k(\varepsilon, \varepsilon') = k_0 \{1 - \beta\varepsilon - \delta\varepsilon^2 - \alpha[\Delta\varepsilon + \varepsilon(t)\,sign(\varepsilon')] + \ldots\} \qquad (2)$$

In Eq. (2), k_0 turns out to be the linear modulus, $\Delta\varepsilon$ is the local strain amplitude over the previous period, ε' is the strain rate, and $sign(\varepsilon') = 1$ if $\varepsilon' > 0$, while if $sign(\varepsilon') = -1$ if $\varepsilon' < 0$.

The parameters β and δ are the classical non-linear perturbation coefficients, and α is a measure of the material hysteresis.

Due to the various non-linear and hysteretic contributions described above, the harmonic spectrum of a finite amplitude mono-frequency wave propagating through the material may exhibit additional harmonics, whose amplitudes depend on the fundamental strain amplitude in different ways, according to the type of non-linearity. In particular, the classical non-linear theory predicts that the second harmonic is quadratic in the fundamental strain amplitude (slope 2 in a log-log plot), while the third harmonic is cubic (slope 3) and so on. On the contrary, the third harmonic should be quadratic for a purely hysteretic material, thus revealing a different response in comparison with classical non-linear materials.

3 EXPERIMENTAL PROGRAM

The theoretical model reported in (Van Den Abeele 2000a-b) was implemented through laboratory experiments. Damage evolution into plain concrete samples was induced by static loading at different stress levels, and subsequently detected using UT.

3.1 *Materials and specimens*

A concrete slab was produced according to the mix composition given in Table 1.

Table 1. Concrete Composition.

Cement Type	CEM II A-L 42.5 R
Cement Proportions	270 kg/m^3
Sand Proportions	1063 kg/m^3
Gravel Proportions	799 kg/m^3
Max. Aggregate Size	16 mm
Water/Cement Ratio	0.74

It was water-cured for 28 days and subsequently air-cured for approximately three years before testing. Core-drilled samples were obtained from this slab. They were consequently cut in order to get cylindrical specimens, approximately 160 mm long and 60 mm in diameter. The mechanical characteristics of the concrete were preliminarily evaluated by means of a uniaxial static compression test, that resulted in a compressive strength of 24 N/mm^2.

3.2 *Testing Equipment*

Static loads were applied by means of a 250 kN servo-controlled material testing machine. The ultrasonic tests for damage characterization were performed by means of the following testing equipment:

- A pair of piezoelectric transducers with a diameter of 35 mm and a work frequency of 55 kHz. One of them was used as the emitting source and the other as the receiving transducer.
- A waveform generator able to produce sinusoidal signals at different frequencies and amplitudes. It was used to drive the emitting source, forcing it to produce a sinusoidal wave at approximately 55 kHz, with varying amplitudes.
- A data acquisition unit, equipped with an oscilloscope for real-time data visualization (Fig. 1). A sampling frequency of 1500 kHz was selected, in the respect of Nyquist's theorem.
- A personal computer for post-processing of the acquired data.

3.3 *Testing Procedure*

An initially undamaged specimen was first subjected to ultrasonic tests aimed at characterizing its intrin-

sic non-linearity. Subsequently, it was subjected to a specific load history, simulating a possible damage process affecting a real structure. Such a load history consisted of the following steps:
- Static compressive loading up to 60% of the estimated compressive strength (σ_R) and unloading.
- Static compressive loading up to 70% σ_R and unloading.
- Static compressive loading up to 80% σ_R and unloading.
- Static compressive loading up to 80% σ_R and unloading.
- Static compressive loading up to 85% σ_R and unloading.
- Static compressive loading up to 90% σ_R and unloading.

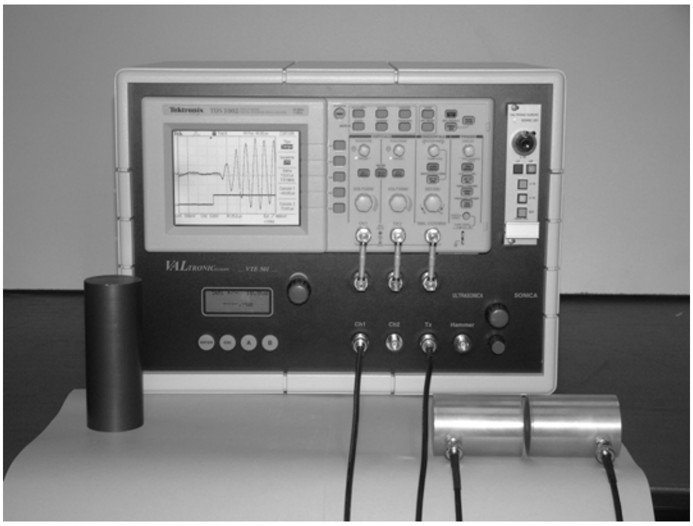

Figure 1. Data acquisition unit and piezoelectric transducers.

At the end of each step, the specimen was subjected to ultrasonic tests. The piezoelectric transducers were applied to the transverse surfaces of the specimen, so that the ultrasonic wave traveled in the longitudinal direction. Special care was devoted to ensure that test conditions remained the same throughout the experiments. In particular, the amount of coupling agent (plasticine) to be used was kept constant, as well as the pressure applied to the transducers.

Preliminary experiments have been conducted to verify the repeatability of the measurements. Also, the linearity of the piezoelectric transducers, within the range of voltages used, has been verified by checking the absence of harmonics generation in a linear steel cylinder under the same experimental conditions.

4 RESULTS AND DISCUSSION

In Figure 2, the results of the load tests are reported in terms of load vs. deformation curves. It can be observed that the material stiffness did not significantly vary as a function of the applied stress.

As far as ultrasonic tests are concerned, it shall be recalled that, according to the theoretical model (Van Den Abeele 2000a-b), the input signal is transformed after passing through the material. More specifically, additional harmonic components are generated, thus revealing possible material non-linearity.

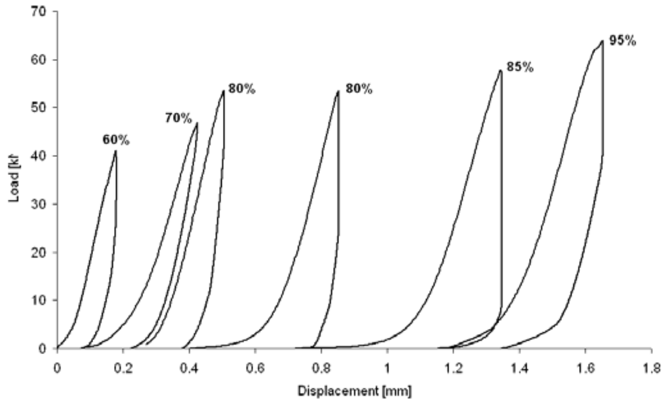

Figure 2. Static load vs. displacement curves for different stress levels.

In order to get information about such a non-linearity, the harmonic components parameters (i.e. amplitude and frequency) need to be evaluated. In the present study, this task was accomplished using two different estimation techniques: a non-parametric one, the well-known Fast Fourier Transform (FFT) (Manolakis et al. 2005), and a parametric one referred to as MUltiple SIgnal Classification (MUSIC) (Schmidt 1986, Stoica & Nehorai 1989, Stoica & Nehorai 1990, Sellone 2000). When a signal is composed by one harmonic component only buried in white Gaussian noise, the FFT technique corresponds to the maximum likelihood estimation of the amplitude, which is also equal to the Least Square method (LS). Unfortunately, the frequency estimation is limited by the points over which the FFT is evaluated. Moreover, in the experiment considered in this paper, more than one harmonic component are simultaneously present, thus calling for different statistically efficient estimation techniques.

The parameters can be better estimated through a parametric approach such as MUSIC. Indeed, it is an efficient frequency estimator, since it provides asymptotically unbiased estimates of a general set of signal parameters, approaching the Cramer Rao bound. By substituting such estimated frequencies back into the original signal model, the problem becomes linear in amplitudes and phases and thus a LS approach can be used to obtain the maximum likelihood estimates. Figures 3 and 4 remark the differences between the two techniques. MUSIC captures more clearly the harmonic components present in the signal.

In both Figures 3 and 4 it is easy to observe harmonics generation, and in particular the presence of the third harmonic which is analyzed here. Odd harmonics are larger than even ones (see Figure 2) indicating dominance of hysteresis or of the second order classical non-linearity (δ term in Eq. (2)). The third harmonic increases considerably when increasing the driving amplitude from 4.4 to 8.1 Volts.

It shall be remarked here that in Figure 3 amplitudes are plotted before the LS calculations and therefore they are not related to the actual harmonic amplitude (not even the ratio of amplitudes at different frequencies is meaningful).

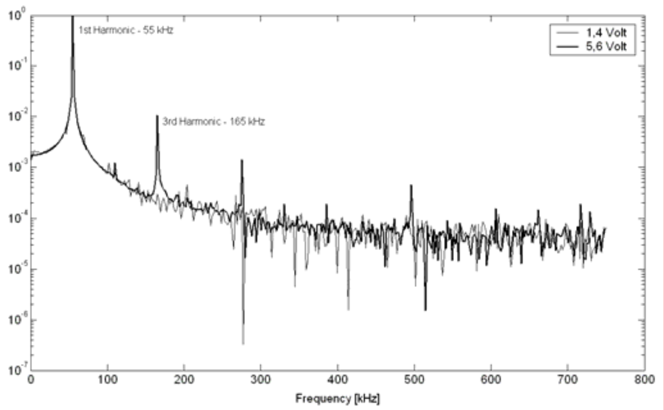

Figure 3. Example of FFT spectrum. *The peaks amplitude represents the actual harmonic amplitude.*

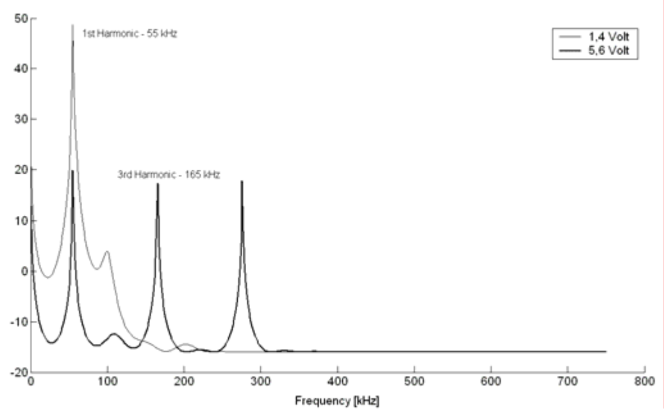

Figure 4. Example of MUSIC pseudospectrum. *The peaks amplitude is not related to the actual harmonic amplitude, which is estimated via LS.*

Consistently with the above considerations, the fundamental and the third harmonic amplitudes at the end of each load step were evaluated by a software-controlled algorithm implementing MUSIC and LS estimation.

The observations were replicated under constant conditions in order to check measurement repeatability. Accordingly, sets of five observations per driving amplitude have been made on a single specimen, at the end of each load step, taking care that ambient and test conditions were kept constant throughout the testing process. As a result, repeated estimates of the fundamental and third harmonic amplitudes were obtained. An example is shown in Figure 5, where the values are plotted of the five fundamental versus third harmonic amplitudes, resulting from five repeated measurements at the end of a specific load step. A very good repeatability was found to exist, since these values are nearly overlapping.

Once that measurement repeatability was ascertained, the amplitude of the third harmonic (165 kHz) and the amplitude of the fundamental one (55 kHz) were evaluated as a function of the driving strain amplitude, for different damage level.

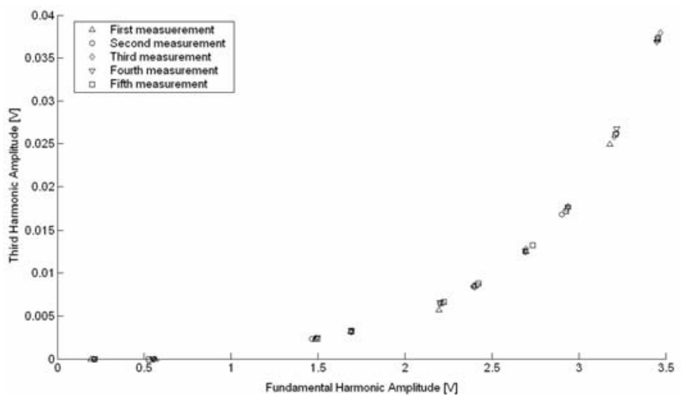

Figure 5. Measurement repeatability.

The results are depicted in Figure 6, where three curves are reported, each one representing the plot of the third harmonic amplitude versus the fundamental one, for varying driving amplitude. The solid line curve corresponds to specimens in the undamaged state, while the dashed-dotted line denotes specimens which had undergone low static loading, that caused a low-damage level, and finally the dotted line corresponds to specimens which had been subjected to a high static stress level, with consequent remarkable damage.

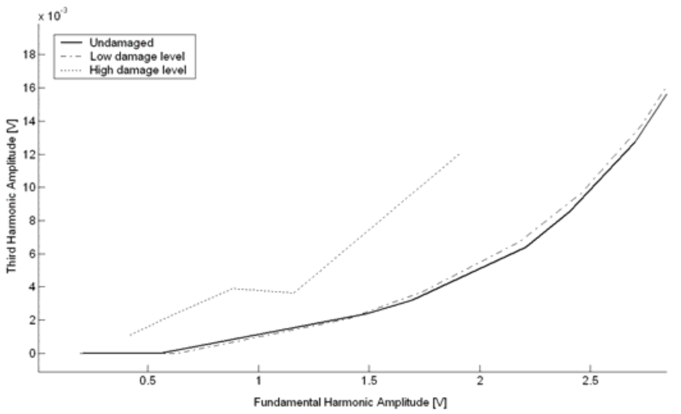

Figure 6. Third vs. fundamental harmonic amplitudes for different damage levels.

Data at low strain amplitudes indicate that the analyzed concrete is characterized by a non-classical non-linear constitutive equation, with presence of hysteresis. In fact, log-log plots seem to indicate that the third harmonic depends quadratically on the fundamental one, while at larger amplitudes classical non-linearities may be dominant (cubic power law dependence). Further investigation to confirm such observation is in progress.

It can also be observed that for low static stress levels, no apparent damage phenomena occurred. Accordingly, no significant differences may be remarked between 1^{st} - 3^{rd} harmonics curves related to specimens in the undamaged state and those related to specimens which had undergone low static loading. On the contrary, more marked differences can be found in visibly damaged specimens, i.e. in specimens subjected to a high static stress level, that caused noticeable macro-cracking occurrences. The increase in non-linearity due to such a damage is revealed by the fact that the third harmonic generation becomes more evident.

5 CONCLUSIONS

The experimental research presented in this paper confirmed the theoretical models concerning the non-linear response of granular materials, such as concrete, when traversed by ultrasonic waves.

The generation of additional harmonic components, and third harmonic in particular, may be as sumed as an indicator of the deterioration state, since experimental evidence revealed that it becomes more marked with increasing level of damage.

The use of novel signal processing techniques such as MUSIC makes it possible to obtain more accurate amplitude and phase estimates for sinusoids in white Gaussian noise than classical FFT, thus revealing to be optimal for the specific problem under consideration. It substantially improves the performances of simple data acquisition systems, such as the one used in the course of this experimental study, thus making the proposed damage assessment technique more attractive.

These encouraging findings suggest to continue the research in order to consider additional types of damaging actions (environmental actions, fatigue, creep, etc.) and extend the proposed method to the on-site evaluation of existing structures.

REFERENCES

Van Den Abeele, K. E. A., Johnson, P. A. & Sutin, A. 2000a. Nonlinear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage. Part I: Nonlinear Wave Modulation Spectroscopy (NWMS). *Res Nondestr Eval* vol. 12 (1): 17-30.

Van Den Abeele, K. E. A., Johnson, P. A. & Sutin, A. 2000b. Nonlinear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage. Part II: Single Mode Nonlinear Resonance Acoustic Spectroscopy. *Res Nondestr Eval* vol. 12 (1): 31-42.

Bentahar, M., El Aqra, H., El Guerjouma, R., Griffa, M. & Scalerandi, M. 2006. Hysteretic elasticity in damaged concrete: Quantitative analysis of slow and fast dynamics. *Physical Review B* vol. 73 (14) 014116: 1-10.

Bocca, P. & Rosa, G. 1993. Hysteretic elasticity in damaged concrete: Frequency spectra and ultrasonic pulse attenuation analysis for the assessment of damages in concrete. *Proc. of the International Conference on Non Destructive Testing on Concrete in the Infrastructure, Dearborn, (Michigan, USA), June, 9 – 11, 1993*: 330-340.

Bocca, P. & Nano, A. 1995. Evoluzione del danneggiamento negli elementi in calcestruzzo: analisi dello spettro di frequenza degli ultrasuoni. *Proc. of the XXIV AIAS National, Parma (Italy), September, 27 – 30, 1995*: 292-299.

Daponte, P., Maceri, F. & Olivito, R. S. 1995. Ultrasonic signal-processing techniques for the measurement of damage growth in structural materials. *IEEE Trans. on Instrumentation and Measurement* vol. 44 (6): 1003-1008.

Daponte, P., Maceri, F. & Olivito, R. S. 1990. Frequency-domain analysis of ultrasonic pulses for the measure of damage growth in structural materials. *Proc. of the IEEE Ultrasonic Symposium 1990* vol. 2: 1113 - 1118.

Pugno, N. & Surace, C. 2000. Evaluation of the non-linear dynamic response to harmonic excitation of a beam with several breathing cracks. *Journal of Sound and Vibration* vol. 235 (5): 749-762.

Schmidt, R. 1986. Multiple emitter location and signal parameter esti-mation. *IEEE Trans. on Antennas and Propagation* vol. 34 (3): 276-280.

Stoica, P. & Nehorai A. 1989: MUSIC, maximum likelihood, and Cramer-Rao bound. *IEEE Trans. on Acoustics, Speech, and Signal Processing* vol. 37 (5): 720-741.

Stoica, P. & Nehorai, A. 1990: MUSIC, maximum likelihood, and Cramer-Rao bound: further results and comparisons. *IEEE Trans. on Acoustics, Speech, and Signal Processing* vol. 38 (12): 2140-2150.

Stoica, P. & Soderstrom, T. 1991: Statistical analysis of MUSIC and subspace rotation estimates of sinusoidal frequencies. *IEEE Trans. on Signal Processing* vol. 39 (8): 1836-1847.

Sellone, F 2006.: Robust auto-focusing wideband DOA estimation. *Signal Processing* vol. 86 (1): 17-37.

Manolakis, G., Ingle, V. K. & Kogon, S. M. 2005. *Statistical and Adaptive Signal Processing*, London: Artech House.