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A Novel Ultrasonic Technique to Detect Damage Evolution in Quasi-Brittle Materials

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Abstract. The results of an experimental research on plain concrete are presented. The non-linear behavior of both virgin and damaged samples is 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 classical or hysteretic 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 micro-cracking, thus suggesting the possibility to use the ultrasonic signal analysis in the frequency domain as a valuable tool for damage assessment.

Introduction

A large amount of European architectural and infrastructure heritage is currently affected by damage phenomena or exposed to high risks of deterioration, especially in seismic areas. This motivates the increasing interest in damage assessment and the demand for non-destructive techniques able to meet the contrasting requirements of accuracy, reliability, cost-effectiveness, ease of use and fast response time. In this regard, ultrasonic techniques have been successfully used all over the world for a long time, due to their non-destructive character and low-cost. Nowadays they play a major role in the complex process of diagnosis and monitoring of materials and structures and their use is regulated by several national and international standards, each one controlling specific applications of these techniques. More recently, the development of sophisticated theoretical models concerning the non-linear behavior of quasi-brittle materials such as concrete or rocks [1-4], and the initiation of powerful signal processing techniques [5-9], encouraged a novel way to approach ultrasonic techniques: the analysis of ultrasonic signals in the frequency domain. Accordingly, some Authors have proposed the spectral analysis of ultrasonic waves as a possible tool to characterize concrete behavior [1-2, 10].

In continuity with these studies, the objectives of the research here presented are the following:

- developing an experimental procedure able to implement the existing models for concrete;
- evaluating the possibility to apply this procedure to the damage assessment of concrete, based on the results of laboratory experiments;
- investigating the most appropriate signal processing techniques in order to optimize the use of currently available systems for signals generation and acquisition, so as to make the proposed procedure economically competitive.

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; finally, the experimental results are reported and discussed.

Theoretical Background

Non-linearity in the elastic behavior of a material is known to be deeply dependent on the level of micro-cracking and damage affecting the material itself. 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 [2]. 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:

$$\sigma = \int k(\varepsilon, \varepsilon')\, d\varepsilon \tag{1}$$

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

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

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

Laboratory Testing

The theoretical model reported in [1-2] was implemented through laboratory experiments. Damage evolution into plain concrete samples was induced by both static and cyclic loading, and subsequently detected using ultrasonic signal analysis in the frequency domain.

Materials and Specimens. A concrete slab was produced using a CEM II A-L 42.5 R cement, ordinary aggregates (max. size = 16 mm) and a water to cement ratio equal to 0.74, with no admixtures. 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.

Testing Equipment. Static and cyclic 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. 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.

Testing Procedure. An initially undamaged specimen was first subjected to ultrasonic analyses aimed at characterizing its intrinsic 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).
- Cyclic compressive loading (σ_{max} = 60% σ_R; σ_{min} = 0; frequency = 2 Hz; cycles = 3600).
- Static compressive loading up to 70% σ_R.
- Cyclic compressive loading (σ_{max} = 70% σ_R; σ_{min} = 0; frequency = 2 Hz; cycles = 3600).
- Static compressive loading up to 80% σ_R.
- Cyclic compressive loading (σ_{max} = 80% σ_R; σ_{min} = 0; frequency = 2 Hz; cycles = 3600).
- Static compressive loading up to 90% σ_R.

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 repeatibility 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.

Results and Discussion

In Fig. 1, 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.

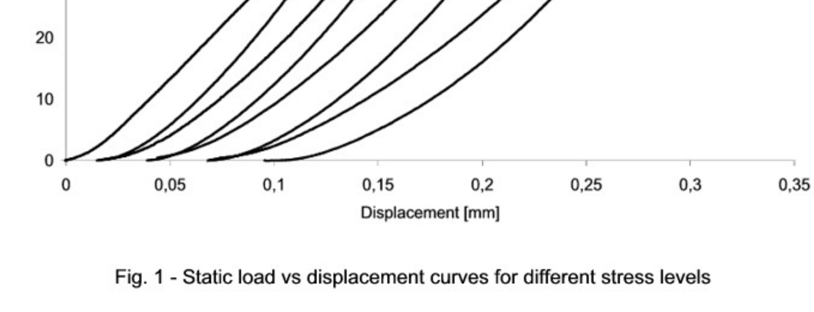

Fig. 1 - Static load vs displacement curves for different stress levels

As far as ultrasonic tests are concerned, it shall be recalled that, according to the theoretical model [1-2], the input signal is transformed after passing through the material. More specifically, additional harmonic components are generated, thus revealing possible material non-linearity. 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) [11], and a parametric one referred to as MUltiple SIgnal Classification (MUSIC) [5-9]. 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).

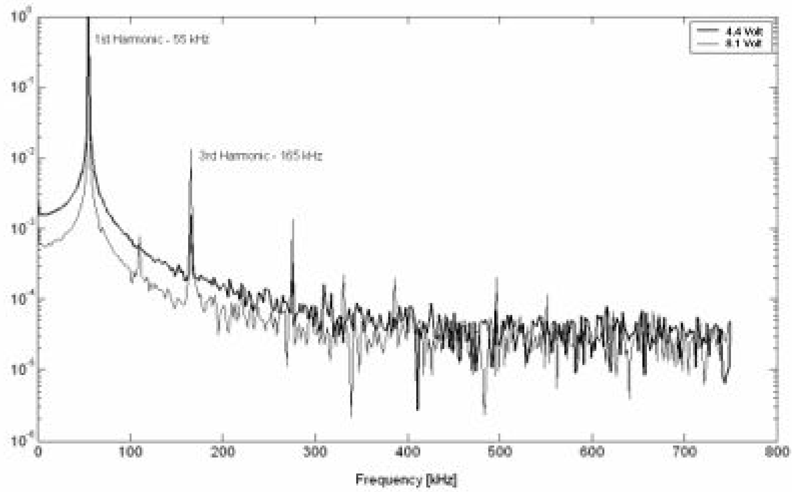

Fig. 2 - Example of FFT Spectrum
The peaks amplitude represents the actual harmonic amplitude

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. Figs. 2 and 3 remark the differences between the two techniques. MUSIC captures more clearly the harmonic components present in the signal.

In both Figs. 2 and 3 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 Fig. 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 Fig. 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).

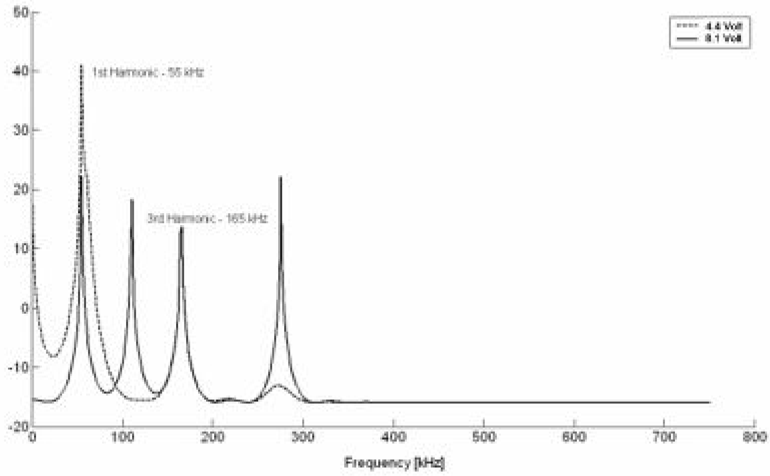

Fig. 3 - Example of MUSIC Pseudospectrum
The peaks amplitude is not related to the actual harmonic amplitude which is estimated via LS

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 amplitude of the third harmonic (165 kHz) is reported vs. the amplitude of the fundamental (55 kHz) in Fig. 4.

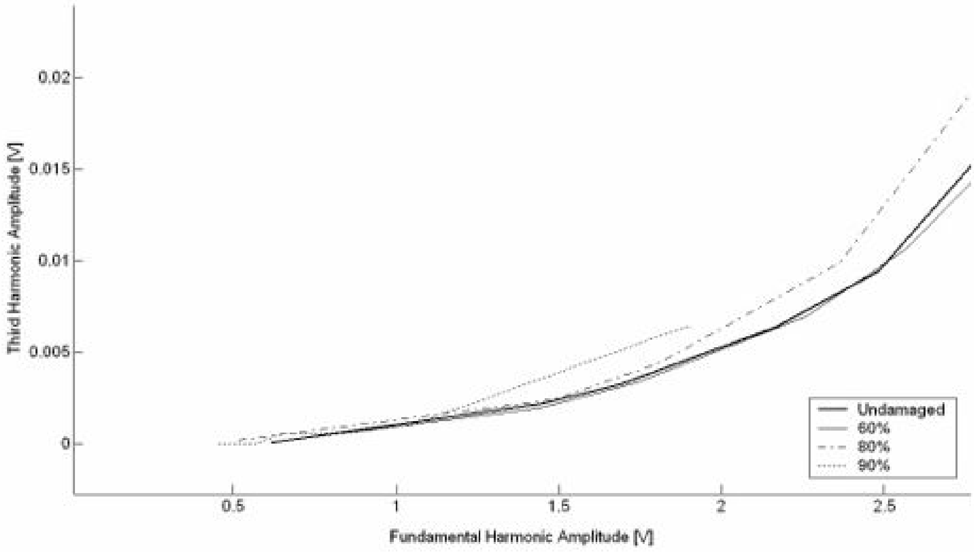

Fig. 4 - Third vs fundamental harmonic amplitude in the undamaged state and at the end of static load tests at different stress levels

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 the applied load history did not cause marked macro-cracking phenomena, but at most micro-cracking occurrences, which are not at all revealed by the quasi-static curves of Fig. 1. In any case, it can be expected that the loading would induce an increase in the internal damage level and consequently in the material non-linearity, which is revealed by the fact that the third harmonic generation becomes more evident. It follows that the proposed method appears to be suitable to assess even early-stage damage.

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 assumed as an indicator of the damage level, since experimental evidence revealed that it becomes more marked with increasing level of internal micro-cracking.

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.

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