NONLINEAR PHENOMENA ANALYSIS IN THE ULTRASONIC WAVE PROPAGATION TO DETECT DAMAGE EVOLUTION IN HISTORICAL STRUCTURES

Paola Antonaci (1), Pietro Bocca (1), Caterina Bruno (1), Davide Masera (1), Antonio S. Gliozzi (2) and Mario Scalerandi (2)

(1) Department of Structural Engineering and Geotechnics, Politecnico di Torino, Italy
(2) Department of Physics, Politecnico di Torino, Italy

Abstract
The non-linear behaviour of both virgin and damaged samples is experimentally investigated by means of ultrasonic tests. Generally, the signatures of non-linearity in the elastic response of a specimen stressed by an ultrasonic wave is analysed by means of classical Fourier analysis. The main problem is related to the low amplitude responses obtained, often below the noise level. For this reason, in this paper a novel and alternative tool, based on the amplitude dependence of the response of the system, is presented. The sensitivity of the approach to the presence of non-linearity is proven experimentally onto several linear and non-linear material and an application on a granite slab is shown.

Keywords
Ultrasonic technique; non-linear spectral analysis; signal processing; damage; granular materials.

1. INTRODUCTION
European monumental and historical constructions are often seen to be in poor repair conditions and exposed to high risks of deterioration, especially in seismic areas. For the preservation of these monuments it is necessary to assess their durability by taking account cumulative damage and cracking conditions in the structures. Many non-destructive techniques have been developed in recent years to this end. Among them, Ultrasonic Techniques (UT) have been successfully used in granular materials (concrete, granite, etc.) to deduce its quality and extent of micro and macro-cracking. Crack detection is usually carried
out by measuring pulse velocity or resorting to impact echo methods and others (Popovic & Popovic 1992). Monitoring the crack growth and damage evolution in granular materials in terms of the non-linear response to the application of ultrasonic waves has been more recently proposed, revealing to be fairly sensitive (Van Den Abeele et al. 2000a-b; Bentahar et al. 2006) to the presence of early stage damage. A system excited with a fixed frequency and with an internal micro-damage respond with the same frequency of the excitation, plus contributions at different frequencies. Nonlinear signatures can be observed in term of either higher order harmonics (Van Den Abeele & De Vissche 2000; Van Den Abeele et al. 2001) or sidebands (Ulrich et al. 2007). In both cases, nonlinear features can be extracted by band-pass filtering the recorded signal in order to cancel contributions at the excitation frequency. Alternatives have been developed using non-parametric techniques, the well-known Fast Fourier Transform (FFT) analysis (Van Den Abeele et al. 2004), parametric tools such as the MUltiple SIgnal Classification (MUSIC) (Antonaci et al. 2007; Antonaci et al. 2007) and phase-coded subtraction methods (Goursolle et al. 2007) or analysis of the phases of the signal (Vila et al. 2004). Nevertheless, these approaches are not always suitable, because several technical and theoretical problems have to be considered, such as the intrinsic nonlinearity in the generation/acquisition system (Ulrich et al. 2006). Moreover, the amplitude of nonlinear contributions for instance higher order harmonics or sidebands often falls within the noise level, unless receiver are located close to the damaged zone.

The Scaling Subtraction Method (SSM) (Scalerandi et al. 2008), as a novel nonlinear approach, is discussed here. This method is based on comparing a low amplitude “reference signal”, which corresponds to the linear response, with large amplitudes signals, which correspond to the nonlinear responses. An experimental program is planned to evaluate the performances offered by this procedure in damage assessment of granular materials, such as concrete and granite. Firstly, in order to test the method sensitivity, the laboratory experiments have been conducted on several materials such as steel, mortar, intact concrete, high and low damaged concrete. Subsequently, the SSM method has been applied to a granite slab with a contact vein to characterize its intrinsic nonlinearity.

2. SCALING SUBTRACTION METHOD

Different constitutive equations can be used to model the propagation of elastic waves in a nonlinear medium (Baltazar et al. 2002; Delsanto & Scalerandi 2003). The main interest in this paper consists in exploiting the information contained in the “common to all models” scaling properties of the solution with respect to the amplitude of the excitation:

- the presence of nonlinearity causes a wave distortion with the appearance of frequencies which are multiple of the fundamental frequency $\omega_0$ of the signal injected at the source;
- when a wave travels in the nonlinear region of the material, the wave speed becomes amplitude dependent, since such are the material elastic constants. For this reason, different portions of the signal travels at different speeds, with a resulting distortion of the wave. At the receiver, the wave arrives with a phase dependent on the amplitude and extension of the nonlinear region encountered;
- the elastic energy of the signal is redistributed among the multiple frequencies and energy losses increase with the amplitude signal. In any case, an amplitude dependent loss in terms of energy at $\omega_0$ is observed.
Having denoted with $A$ and $\omega_0$ the amplitude and the fundamental frequency of the injected signal (assumed for simplicity to be a monochromatic wave), the signal received at the transducer, denoted as $v_A(t)$, is given by:

$$v_A(t) = \sum_{n=1} B_n(A) \cos(n\omega_0 t + \varphi_n(A))$$  \hspace{1cm} (1)

In the limit of small $A$, the nonlinear contributions are negligible and it is possible to define/measure at the receiver a signal containing only linear signatures, called “reference signal”:

$$v_{lin}(t) = B_1(A \rightarrow 0) \cos(\omega_0 t)$$  \hspace{1cm} (2)

Let us now discuss our approach: first the specimen is excited with a low amplitude ($A_{lin}$), in order to detect the “reference signal”. If the amplitude is very small, Equation 2 is valid. Afterward, the sample is excited with a larger amplitude $A = k A_{lin}$ detecting a signal $v_A(t)$ in the form of Equation 1. The nonlinear response is given by the following equation:

$$w_A(t) = v_A(t) - k v_{lin}(t)$$  \hspace{1cm} (3)

Equation 3 is the result of a simple subtraction between Equation 1 and Equation 2 where $w_A(t)$ contains the higher order harmonics of $v_A(t)$, plus contributions at $\omega_0$ with amplitude dependent on the phases and on the nonlinear attenuation. If the material is perfectly linear, $w_A(t)$ is null (except for noise effects). It is evident that, $w_A(t)$ contains more energy and informations about the nonlinear scatterers than that contained when a simple band-pass filter is used, which identifies nonlinear features through a signal:

$$w_f(t) = B_1(A \rightarrow 0) \cos(\omega_0 t)$$  \hspace{1cm} (4)

In addition, $w_A(t)$ has the additional advantage with respect to $w_f(t)$ of being derived by a simple subtraction method. On the other hand, the filtering process is always based on a complex mathematical approach, where the results are often influenced by the choices of the length and sampling of the signal and by the choice of the windowing procedures. Finally, this solution has also advantages with respect to methods which allow the selection of contribution to the signal due to a single harmonic without the need of any FFT, e.g. the phase-coded subtraction methods (Goursolle et al. 2007).

3. EXPERIMENTAL VALIDATION OF SSM

In order to apply the theoretical model proposed in the previous section and recently presented (Scalerandi et al. 2008), a laboratory experiment was performed. To validate the SSM, a series of UT tests on several linear and nonlinear specimens (steel, mortar, intact concrete, high and low damage concrete) were carried out.

3.1 Materials, Specimens and Testing Equipment

Samples of different materials have been prepared in the shape of cylinders 160 mm long and 60 mm in diameter.

The ultrasonic tests have been performed using the following testing equipment:
3.2 Testing Procedure
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.

4. RESULTS AND DISCUSSION
Each sample has been characterised by a set of signals $w_i(t) = v_i(t) - k_i v_1(t)$, where $k_i$ are the ratios of the corresponding input voltages (recorded at the generator). In Figure 2a, the signals $v_{13}(t)$ and $k_{13} v_1(t)$ for the intact concrete and steel specimens are analysed. In the concrete specimen, the phase delay and amplitude differences of $v_{13}(t)$ with respect to the rescaled linear signal are marked. Instead, in the steel specimen these differences are negligible, as expected being the steel specimen linear in the voltage range considered here. The energy contained in the scaling subtracted signal ($w_{13}(t)$) is of the same order of that of the recorded signal. For an accurate analysis, two quantitative parameters for $w_i(t)$ have been defined:
\[ \alpha_i = \max\{w_i(t)\} \]  
\[ \beta_i = 1/T \int_0^T w_i^2(t) \, dt \]  

Figure 2: Recorded temporal signals in the intact and steel sample at the lower (dashed line) and larger (solid line) input voltage (a). Amplitude indicator \( \alpha \) of the subtracted signal vs. energy of the recorded output signal for several materials (b).

The two parameters are related to the amplitude and energy of the subtracted signal, respectively. In Figure 2b, the parameter \( \alpha_i \) is plotted vs. the energy of the output amplitude signal \( v_i(t) \) for five samples (steel, mortar, intact concrete, high and low damage concrete). \( \alpha_i \) increases rapidly with increasing the energy of the recorded output signal for all the specimens considered. The plot allow to discern the small classical non linearity present in the steel sample respect to the greater one of the other samples.

5. APPLICATION OF SSM TO A GRANITE SLAB

In this section, it is shown an application of SSM to a granite slab in order to mark a natural veining respect to the presence of internal defects such as microcracks. In many cases, microcracks present the same visual features of natural veins in the specimen. It is therefore important to develop tools, different from a simple visual inspection, to distinguish between the two: in fact only microcracks can lead to problems when the granite is used in structures or for restoration of historical structures.

5.1 Granite slab: extraction site, mineralogical composition and geometry features

The Linyi granite was extracted in a strip pit in Zhangzhuang town (Yinan county, China). The landform of the mine is massif with height between 130 and 170 meters above the sea level. The granites of this mine were formed at Mesozoic era. The main compositions of the granite are plagioclase, pyroxene and a little biotite. Chemical composition and physical properties of the granite slab are shown in Table 1.
The granite slab measures 1000 x 800 x 160 mm$^3$ (Figure 3). It is possible to observe a natural veining on the four faces of the slab.

### 5.2 UT measuring and results

The piezoelectric transducers were applied to the transverse surfaces of the slab, so that the ultrasonic wave travelled in the thickness slab direction. UT measuring was performed scanning the whole height of the granite slab, always with perfect alignment between the emitting and receiving transducers. As a result, a series of UT measures was carried out both in veining and intact region, as shown in Figure 4. Experiments have been conducted varying the signal amplitude between 10V and 70V, with 5 Volts step. The frequency of the sinusoidal wave was 55 kHz.

#### Table 1: Chemical composition and physical properties of the granite slab

<table>
<thead>
<tr>
<th>CHEMICAL COMPOSITION</th>
<th>PHYSICAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Dioxide (SiO$_2$)</td>
<td>51.13%</td>
</tr>
<tr>
<td>Alluminium Oxide (Al$_2$O$_3$)</td>
<td>14.19%</td>
</tr>
<tr>
<td>Calcium Oxide (CaO)</td>
<td>9.67%</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>8.16%</td>
</tr>
<tr>
<td>Ferric Oxide (Fe$_2$O$_3$)</td>
<td>7.97%</td>
</tr>
<tr>
<td>Sodium Oxide (Na$_2$O)</td>
<td>3.01%</td>
</tr>
<tr>
<td>Iron Monoxide (FeO$_2$)</td>
<td>2.22%</td>
</tr>
<tr>
<td>Sulphuric Anhydride (SO$_3$)</td>
<td>0.04%</td>
</tr>
<tr>
<td>other</td>
<td>3.61%</td>
</tr>
</tbody>
</table>

Figure 3: Geometric features of the veining trace onto the four faces of the granite slab and a view of the slab
The results in term of nonlinearity assess in granite slab are shown in Figure 5a, where $\beta_i$ is plotted vs. the energy of the input signal for each amplitude level. The $SSM$ data analysis indicates no relevant differences between veining (points A3, C3, E3) and intact (points H3, M3, P3, S3) regions. The curve related to the point H3 presents an anomalous trend respect the other curves. This result is due to the presence of a steel insert in the slab close to the measurement point. As a conclusion of our measurements, the nature of the veining appears to be not nonlinear. For this reason, the granite veining is not an internal defect such as a microcrack.

A second parameter was evaluated to estimate the nonlinear features of the granite slab: the amplitude of the third harmonics of the signals generated from the material nonlinearity. As a matter of fact, it has been observed that material non-linearity causes distortions in the propagation of elastic waves, creating accompanying harmonics and multiplication of waves at different frequencies. The theoretical model has been described in (Antonaci et al. 2007). The results of our measurements on the granite slab are reported in Figure 5b, where the third harmonic amplitude is plotted vs. the amplitude of the input signal. Confirming the results of the SSM method, the presence of higher order harmonics is negligible both in veining and intact regions. This means again that the non-linearity signatures are too small.

**Figure 4:** The seven points onto granite slab where UT measures have been evaluated

**Figure 5:** Energy of the scaled signal ($\beta_i$) vs. energy of the input signal (a). Third harmonic amplitude vs. input amplitude (b)
6. CONCLUSIONS

A new method for detection of the non linear signatures was presented. The Subtraction Scaling Method is very sensitive to the presence of nonlinearity such as micro-crack. The maximum amplitude or energy of the scaling subtracted signal may be assumed as an indicator of the non-linear state of the material, since experimental evidence revealed that they become more marked with increasing the level of nonlinearity. The analysis of the granite slab highlights that the SSM can be a useful and simple method to investigate the presence of micro and macro internal defects. These encouraging findings suggest to continue the research in order to extend the proposed method to the on-site evaluation of existing structures.

REFERENCES

