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A new method to assess the ultrasonic attenuation in samples with non-distinguishable echoes

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The progressive energy loss experienced by the signals as they propagate through the material is mainly due to two mechanisms: energy absorption and scattering. Attenuation is usually measured from the echoes observed on the A-scan which originates from reflections in the material. This paper describes a new method of quantifying the attenuation of ultrasonic waves in samples whose nature makes it impossible to distinguish reflections.

The attenuation is quantified in terms of the time taken to receive the energy, expressed as a multiple of the time of flight TOF (n·TOF). The method starts from the A-scan data taken from the moment at which the signal begins to be received until its complete attenuation. The received energy is related to the square of the amplitude of the ultrasonic wave. This value of the energy is plotted versus n·TOF, noting the values of n times the TOF at which 10%, 20%, ..., 90% of the total energy received are reached.

The paper includes a checking of the method by its use in different specimens (cubic samples of granite and raw samples of pork loins). The results show interesting relationships between the new attenuation values and other non-ultrasonic parameters of the specimens.
I. Introduction
Ultrasonic pulse attenuation is a measure of the progressive energy loss experienced by the signals as they propagate through the material. This loss is mainly due to two mechanisms: energy absorption (mainly corresponding to thermo-elastic effects) and scattering (effects of reflection of the pulse front at discontinuities in the material) [1]. In the phenomenon of attenuation, the waves undergo scattering of their energy in all directions due to inhomogeneities in the medium through which they are propagating. These inhomogeneities can correspond to discontinuities such as grain boundaries, pores, and possible fissures. Furthermore, it is known that the variation of attenuation with frequency depends on the relationship between wavelength and grain size [2].

Attenuation is usually measured from the echoes observed on the A-scan which originate from reflections in the material. Unfortunately, given that the nature of some specimens makes it impossible to distinguish reflections, the attenuation cannot be calculated in such a way. The aim of the present study is to introduce and validate a new procedure to analyze attenuation by means of a quantitative metric that enables feasible the determination of this ultrasonic parameter in such kind of samples.

II. Materials and methodology
For the present study, a set of very different specimens have been selected, in particular, different varieties of granite and raw samples of pork loins.

For granites, the ten varieties tested were 30-cm cubes with a polished finish, which reduces their surface porosity and facilitates the penetration of ultrasound. For pork loins, samples were bought in a local Spanish supermarket. The loins were then frozen for 24h to avoid the pieces deforming before cutting, followed by slicing using a MAINCA BM-170 meat saw into samples of approximately 3 cm thickness. Measurements were made inside a temperature-controlled chamber (RIVACOLD RC325-45ED, Italy), increasing or decreasing the temperature depending on whether the sample was frozen or thawed pork loin. The samples were placed so that the ultrasound measurements were made perpendicularly to the muscle fibres. Two measurement temperatures were used, one with the sample frozen at -6°C and the other with the sample thawed at 10°C.

The granite and pork loin samples were inspected ultrasonically using contact techniques in through-transmission (T-T) mode. Figure 1 shows schematically the set-up used for the measurements. The transducers were mounted on a custom-designed metal structure that ensured their perfect face-to-face alignment, also reducing the risk of other errors being introduced by the operator, primarily those due to variations in the pressure exerted on the specimens with the transducers and to involuntary movements by the operator [3]. In addition, the pork loin samples were also tested in pulse-echo (P-E) mode.

![Figure 1: Set-up for the measurements of samples](image-url)
Pairs of PANAMETRICS-NDT piezoelectric transducers from Olympus of different natural resonance frequencies were used in the transmission of the signals. Table 1 lists the principal characteristics of the different transducers used, including the near-field zone and the beam spread angle. Since both values depend on the propagation medium, in Table 1 we provide approximate values for different specimens studied in this work considering a mean ultrasonic pulse velocity UPV of 4500 m/s for granites and 1677 m/s for pork loins.

Table 1. Characteristics of the different transducer models used. UPV=4500m/s and 1677 m/s, for granite and pork loin samples, respectively, are considered in the calculation of $N$ and $\phi$.

<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter (cm)</th>
<th>Frequency (kHz)</th>
<th>-6 dB Bandwidth (%)</th>
<th>Specimen</th>
<th>$N$ (nearfield length) (cm)</th>
<th>$\phi$ (Beam angle) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1012</td>
<td>3.8</td>
<td>250</td>
<td>83</td>
<td>Granite</td>
<td>2.0</td>
<td>35.30</td>
</tr>
<tr>
<td>V189-RB</td>
<td>3.8</td>
<td>500</td>
<td>107</td>
<td>Granite</td>
<td>4.0</td>
<td>16.79</td>
</tr>
<tr>
<td>V1011</td>
<td>3.8</td>
<td>100</td>
<td>67</td>
<td>Pork loin</td>
<td>2.2</td>
<td>32.58</td>
</tr>
<tr>
<td>DHC703</td>
<td>1.3</td>
<td>1 MHz</td>
<td>32.25</td>
<td>Pork loin</td>
<td>2.5</td>
<td>9.05</td>
</tr>
</tbody>
</table>

On the one hand, V1011, V1012 and V189 transducers were connected to the PANAMETRICS-NDT Model 5058PR Pulser-Receiver from Olympus. On the other hand, for DHC703 transducer, the ultrasound signals were emitted and received using an Olympus Pulser-Receiver Panametics-NDT Model 5077PR.

For the acquisition and digitization of the signals from the test of samples, the pulser-receiver was connected to a TDS1012B oscilloscope from Tektronix (100 MHz bandwidth, 1 GSa/s sample rate, 2.5 k points record length) in case of samples of granite. The connection was to an InfiniiVision DSO-X 3032A oscilloscope from KEYSIGHT (350MHz bandwidth, 4 GSa/s sample rate, 10 k points record length) in case of pork loin ones. Both oscilloscopes transferred the data of the displayed signals to a laptop computer, where they were stored for subsequent processing and analysis.

Attenuation is usually measured from the echoes observed on the A-scan which originate from reflections in the material. Then, the attenuation coefficient $\alpha$ (neper/m) is computed as:

$$\alpha = \frac{1}{2d} \ln \left( \frac{A_i}{A_{i+1}} \right)$$

where $A_i$ and $A_{i+1}$ are the (peak-to-peak) amplitudes of echoes $i$ and $i+1$, respectively, and $2d$ represents the space covered by the ultrasound wave between them.

Unfortunately, given that the nature of the specimens corresponding to samples of granite and pork loins, cited in this survey, makes it impossible to distinguish reflections, the attenuation cannot be calculated in such a way. For them, a new procedure has been developed based on the signal’s progressive energy loss. This loss is quantified in terms of the time taken to receive the energy, expressed as a multiple of the time of flight $TOF (n \cdot TOF)$, where $TOF$ is the time lapsed from the signal’s emission until its reception.

As illustrated in the example of Figure 2 (part a), to determine the attenuation, the A-scan data are taken from the moment at which the signal begins to be received ($t=0$) until its complete attenuation, omitting the trigger signal. The received energy is related to the square of the amplitude of the ultrasonic wave. Then, part b of Figure 2 shows the cumulative energy, which is the integral of the squared amplitude over time from $t=0$ to $t=n \cdot TOF$ (normalized by the total energy: integration from 0 to infinity). This value of the energy is plotted versus $n \cdot TOF$, noting the values of $n$ times the $TOF$ at which 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of the total energy received are reached (part b). As such, one can obtain the mean value of the attenuation as a function of the reception time of the energy percentages, for each specimen, with the transducers ($t_{10}$, $t_{20}$, $t_{30}$, $t_{40}$, $t_{50}$, $t_{60}$, $t_{70}$, $t_{80}$, $t_{90}$). By way of explanatory example, a value of $t_{40}$ equal...
to 2.07 would indicate that 40% of the total energy has been received in a time equal to the first 2.07 times the TOF. In the same way, a t80 equal to 4.57 would indicate that 80% of the received energy has arrived in the first 4.57 times the TOF. In this way, the greater the value of \( n \cdot TOF \) at the \( t_{xx} \) time, the less attenuative will be the corresponding sample.

![Figure 2: (a) Example of a typical A-scan received by the V1012 transducer. (b) Attenuation curve of the A-Scan shown in (a). The \( t_{40} \) and \( t_{80} \) values of the \( n \cdot TOF \) are expressly indicated.](image)

### III. Results and discussion

Table 2 shows the coefficients of linear correlation obtained when fitting a straight line through the \( t_{90} \) values corresponding to each one of the transducers with other technological parameters of the granite samples. The negative slope indicates that, in granite samples with increasing values of these non-technological parameters, the transmitted energy is received in a shorter interval of lapsed time, or, in other words, the denser and stronger granite (in terms of compressive, flexural and impact strength) is more attenuating.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Apparent density (g/cm(^3))</th>
<th>Compressive strength (kg/cm(^2))</th>
<th>Flexural strength (kg/cm(^2))</th>
<th>Impact strength (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1012</td>
<td>-0.544</td>
<td>-0.704</td>
<td>-0.678</td>
<td>-0.750</td>
</tr>
<tr>
<td>V189</td>
<td>-0.408</td>
<td>-0.612</td>
<td>-0.536</td>
<td>-0.780</td>
</tr>
</tbody>
</table>

Table 3 lists the mean attenuation values of the \( t_{40} \), \( t_{50} \), and \( t_{60} \) percentiles for pork loins. Bearing in mind that the greater the value of \( n \cdot TOF \) at the \( t_{xx} \) time, the less attenuative will be the corresponding sample, immediately noticeable is the greater attenuation of the ultrasound waves emitted by the 1 MHz transducer, which is logical. Interestingly, however, the attenuation depended on the inspection temperature. Thus, for the frozen samples, it seems that one can deduce that the attenuation is greater. It seems obvious therefore that the measurement of attenuation described in the present work is severely affected by the inspection temperature. It appears sensible to think that the water content of the samples affects this a priori disparate behaviour. Thus, if the sample has a high water content (raw samples) then the freezing of that water would favour increased attenuation.

### IV. Conclusion

This paper describes a new method of quantifying the attenuation of ultrasonic waves in samples (cubic samples of granite and raw samples of pork loins) whose nature (grain size, geometry, etc.) makes it impossible to distinguish reflections. The results show interesting relationships between the new attenuation values and other non-ultrasonic parameters of the specimens. Thus, it can be stated that, in granite samples with increasing values of some non-technological parameters, the granite
variety is more attenuating. As for pork loins, it seems that if the sample has a high water content (raw samples) then the freezing of that water would favour increased attenuation.

Table 3. Attenuation values corresponding to t40, t50, and t60 values for pork loins (mean ± SD).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transducer</th>
<th>Measurement temperature</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>t40</td>
<td>V1011</td>
<td>-6°C</td>
<td>1.80±0.03</td>
</tr>
<tr>
<td></td>
<td>V1011</td>
<td>10°C</td>
<td>1.94±0.03</td>
</tr>
<tr>
<td></td>
<td>DHC703</td>
<td>10°C</td>
<td>1.07±0.03</td>
</tr>
<tr>
<td>t50</td>
<td>V1011</td>
<td>-6°C</td>
<td>1.97±0.03</td>
</tr>
<tr>
<td></td>
<td>V1011</td>
<td>10°C</td>
<td>2.10±0.03</td>
</tr>
<tr>
<td></td>
<td>DHC703</td>
<td>10°C</td>
<td>1.07±0.03</td>
</tr>
<tr>
<td>t60</td>
<td>V1011</td>
<td>-6°C</td>
<td>2.05±0.03</td>
</tr>
<tr>
<td></td>
<td>V1011</td>
<td>10°C</td>
<td>2.44±0.03</td>
</tr>
<tr>
<td></td>
<td>DHC703</td>
<td>10°C</td>
<td>1.08±0.03</td>
</tr>
</tbody>
</table>

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