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Optimized ultrasonic attenuation measures for non-homogeneous materials

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ABSTRACT

In this paper the study of frequency-dependent ultrasonic attenuation in strongly heterogeneous materials is addressed. To determine the attenuation accurately over a wide frequency range, it is necessary to have suitable excitation techniques. Three kinds of transmitted signals have been analysed, grouped according to their bandwidth: narrowband and broadband signals. The mathematical formulation has revealed the relation between the distribution of energy in their spectra and their immunity to noise. Sinusoidal and burst signals have higher signal-to-noise ratios (SNRs) but need many measurements to cover their frequency range. However, linear swept-frequency signals (chirp) improve the effective bandwidth covering a wide frequency range with a single measurement and equivalent accuracy, at the expense of a lower SNR. In the case of highly attenuating materials, it is proposed to use different configurations of chirp signals, enabling injecting more energy, and therefore, improving the sensitivity of the technique without a high time cost. Thus, if the attenuation of the material and the sensitivity of the measuring equipment allows the use of broadband signals, the combination of this kind of signal and suitable signal processing results in an optimal estimate of frequency-dependent attenuation with a minimum measurement time.

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1. Introduction

Concrete is a non-homogeneous material prepared by mixing cement, aggregates, and water, used mainly in the field of civil and building engineering [1]. Due to its non-homogeneous structure, this material in its hardened state is composed by air voids, interfaces between the aggregates and hydrated cement paste, micro-cracks, and other defects inside its microstructure. For that reason, concrete is a very dispersive material and hard to measure (in order to know its physical and mechanical conditions) indirectly with non-destructive techniques (NDT) [2].

Several authors have tried to test cement-based materials using different NDT in order to characterize the properties of concrete and detect damage by means of monitoring diverse parameters [3–5].

Due to its robustness, one of the most widely used parameters for ultrasonic NDT is the ultrasonic pulse velocity. However, attenuation is considered to be a parameter that is very sensitive to the structural properties of the material. Taking into account that it is a parameter related to the energy of the wave, it is more affected than ultrasonic velocity in an experimental setup, such as by coupling problems between the ultrasonic sensors and the analysed material, and energy losses due to wires, connectors, devices [6–9]. Despite these problems, the determination of the frequency-dependent ultrasonic attenuation, $\alpha(f)$, [6,8,10–12], is a useful parameter due to its sensitivity to many defects in a material (voids, cracks...) and properties, specifically for concrete, where the water to cement ratio and the cement to aggregate ratio are important variables for concrete design and determine its mechanical and physical properties.

Several authors have used different techniques to measure the attenuation in cementitious materials. The typical setup is a through-transmission, where the transmission transducer is excited by an electrical signal to generate an ultrasonic signal. The transmitted signals include narrowband [8,13–15] and broadband signals [6,8,16]. On the one hand, narrowband signals provide good performance against high attenuating materials, due to their high signal to noise ratio (SNR), but they require a large number of measurements to estimate the $\alpha(f)$ curve (one measurement per each point of the curve). On the other hand, broadband signals require much less measurements because they cover a wider frequency range, but are more affected by noise because its energy is distributed over a wider frequency range.

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Using broadband signals implies several advantages. Beyond the practical ones (time cost), there exist real applications which cannot be correctly monitored due to the fact that the system under study varies quickly in time. In such a situations, what is needed is the use of a configuration which allows measuring the attenuation efficiently without losing accuracy. The aims of this paper are to analyse each kind of transmitted signal, to provide an optimal method to obtain the frequency-dependent attenuation, $\alpha(f)$, and to compare the attenuation results achieved by each configuration in a particular real application: measuring Portland cement mortar specimens.

The remainder of this paper is structured as follows. Section 2 describes and mathematically formulates the analysis of two narrowband signals (sinusoidal and burst signals) and a broadband signal (chirp signal), as well as the theoretical and experimental expressions for $\alpha(f)$ in each case. Different configurations for the chirp signal are analysed in order to evaluate their noise immunity. In Section 3 the materials and test layout for the experiment which validates the aforementioned expressions are explained. Section 4 presents the attenuation results and, finally, the conclusions are summarized.

2. Mathematical background

In a through-transmission inspection, the energy spectral density (ESD)[1] of the received signal (in the frequency domain), $S_{rx}(f)$ [dB], can be modeled by

$$S_{rx}(f) = S_{tx}(f) - \alpha_{mat}(f) \cdot d_{mat} - \alpha_{equip}(f) \tag{1}$$

where $S_{tx}(f)$ [dB] is the ESD of the transmitted signal, α_{mat} [dB/cm] is the attenuation produced by the specimen, d_{mat} [cm] is the distance between both transducers, and $\alpha_{equip}(f)$ [dB] is the attenuation due to the measuring equipment (amplifier, wires, and frequency response of the emitter and receiver).

From Eq. (1), the attenuation $\alpha_{mat}(f)$ [dB/cm] of the material can be obtained in terms of the other variables, yielding

$$\alpha_{mat}(f) = \frac{10\log(S_{tx}(f)) - 10\log(S_{rx}(f)) - \alpha_{equip}(f)\ [\mathrm{dB}]}{d_{mat}}. \tag{2}$$

The challenge of this study lies in the estimation of the $S(f)$, which relates the transmitted energy/power and received energy/power as a function of frequency. The following aspects must be taken into account.

The signal to noise ratio (SNR) is directly proportional to the sensitivity of the attenuation parameter. Therefore, the kind of transmitted signal and its energy distribution in the frequency domain will affect the accuracy of the method. Working with sinusoidal or burst signals, the energy will be concentrated in a narrow band (higher SNR), but the estimation of $\alpha_{mat}(f)$ will correspond only to that narrow bandwidth. Consequently, in order to cover a wide spectrum, it is required to employ a higher number of input signals varying the fundamental frequency (f_0). On the other hand, in the case of a chirp signal, the energy will be distributed over a wider band (lower SNR) and the estimation of $\alpha_{mat}(f)$ covers a higher range of frequencies with a single input signal. It must be noticed that a good characterization of a highly attenuating material could require the use of signals with a high density energy. In Fig. 1, the temporal and frequency domains of the three types of signals are shown. It can be easily appreciated how the density of energy of the sinusoidal and burst signals is higher than that of the chirp signal.

[1] The energy spectral density, $S(f)$, of a finite time signal, $x(t)$, is defined as $S(f) = |X(f)|^2$, where $X(f) = \int_{t_0}^{t_1} x(t)e^{-j2\pi ft}dt$ is the Fourier Transform of the signal $x(t)$.

The frequency response of the equipment and, mainly, of the transducers, $\alpha_{equip}(f)$, limits the bandwidth that they are able to manage. Usually, the best performance is obtained at the fundamental frequency of the transducer, but it is also possible to work on the pass-band taking into account the required calibration process. The choice of the fundamental frequency depends on the material under inspection.

In this paper, the aforementioned transmitted signals are analysed and proposed for evaluating the attenuation of the material, $\alpha_{mat}(f)$, in order to compare their accuracies and time costs. To obtain $\alpha_{mat}(f)$, it will be necessary to estimate the power/energy of the transmitted and received signals as well as the attenuation introduced by the equipment. The power/energy of the transmitted signal will be computed from its well-known theoretical expressions. However, the power/energy of the received signal will be estimated from the real acquired signals digitalized by the oscilloscope. The attenuation of the equipment will be obtained by the calibration process described in Section 3.3.

2.1. Sinusoidal signal

The theoretical model of a transmitted pure sinusoidal signal is

$$s_{tx}(t) = A_{tx}\cos(2\pi f_0 t + \phi_{tx}), \tag{3}$$

where A_{tx} is the amplitude of signal, f_0 is its fundamental frequency, and ϕ_{tx} is its phase, which will be assumed null. An example is shown in Fig. 1, where the selected parameters for are $A_{tx} = 10$ and $f_0 = 200$ kHz. It is accepted that this signal is periodic, and therefore, it has an infinite time duration.

The theoretical spectrum of this signal (Eq. (4)) gives the power contributed by a single frequency, shown in Fig. 1. The power of this signal (P_{tx}) can be estimated directly from its amplitude, A_{tx} (Eq. (5)). It has been assumed that the propagation medium, equipment, and transducers behave linearly. This implies that no new frequency components will be generated, and the received signal will be the same as the input signal except with a different amplitude and phase, which will depend only on the behaviour of the material and equipment, so that the power of the received signal can be estimated from the amplitude of the received sinusoidal signal, $A_{rx}^{(f_0)}$ (Eq. (6)).

$$S_{tx}(f) = \left|\frac{A_{tx}}{2}(\delta(f-f_0) + \delta(f+f_0))\right|^2 \tag{4}$$

$$P_{tx} = \frac{A_{tx}^2}{2} = \frac{\max\{s_{tx}^2(t)\}}{2} \tag{5}$$

$$s_{rx}(t) = A_{rx}^{(f_0)}\cos\left(2\pi f_0 t + \phi_{rx}^{(f_0)}\right) \rightarrow P_{rx}^{(f_0)} = \frac{\left(A_{rx}^{(f_0)}\right)^2}{2} \tag{6}$$

Hence, the attenuation due to the material for the input frequency $\alpha_{mat}(f_0)$ can be calculated by using both Eqs. (5) and (6), resulting in the following equation:

$$\alpha_{mat}(f_0) = \frac{P_{tx}\ [\mathrm{dB}] - P_{rx}^{(f_0)}\ [\mathrm{dB}] - \alpha_{equip}(f_0)\ [\mathrm{dB}]}{d_{mat}} = \frac{10\log_{10}\left(\frac{A_{tx}^2}{2}\right) - 10\log_{10}\left(\frac{\left(A_{rx}^{(f_0)}\right)^2}{2}\right) - \alpha_{equip}(f_0)\ [\mathrm{dB}]}{d_{mat}} \tag{7}$$

In order to obtain the values of the $\alpha_{mat}(f_0)$ curve, it is required to do a sweep of the input fundamental frequency (f_0). The described calculations must be repeated as many times as the

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