An Advanced Ultrasonic Method based on Signal Modality for Structural Damage Characterization on Concrete: The Cube Problem

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Abstract—In this study, a new approach for characterizing material damage using ultrasonic waves is proposed. Four concrete cubes were subjected to different uniaxial loads (0 %, 25 %, 50 % and 75 %) and evaluated using a novel Recurrence Plot Quantification Analysis (RQA) method. This brand new technique was compared to traditional ultrasonic measures: propagation velocity and attenuation. Both the traditional measures and the brand new technique successfully identified the level of damage in direct configurations. In the case of indirect measurements, the corresponding level of damage was accurately identified by the new proposed technique but not by the traditional ones. The typical pyramid-cracking pattern and its exhibited asymmetry due to the concrete heterogeneity has been perfectly analysed in terms of determinism when dispositions in indirect configurations were compared.

I. INTRODUCTION

Concrete is the most important material used in the construction industry for building and civil engineering. It is a heterogeneous medium composed of different materials with different mechanical and chemical properties that complicate ultrasonic inspections. Due to the important role that concrete plays in building structures, it is necessary to develop new ultrasonic techniques that afford robust results and an accurate diagnosis. In this study, a new approach based on the signal modality of ultrasonic waves is proposed. A complex damage in concrete cube specimens under different axial loads was assessed using such new technique and comparing the results with traditional ultrasonic parameters: ultrasonic pulse velocity and attenuation.

The remainder of this paper is organized as follows. The new approach based on the signal modality characterization is discussed in Section II. Section III presents the tested material, experimental issues as well as the traditional ultrasonic measures carried out to characterized them. Section IV describes the obtained results for all the analyzed configurations and the ultrasonic measurements. The results of the predictability are discussed and compared to the previously known techniques. Finally the conclusions are summarized in Section V.

II. MATHEMATICAL BACKGROUND

In the field of dynamical systems, the concept of the state space reconstruction (SSR) of a signal allows the study of the underlying system. The SSR of the ultrasonic signals is proposed in order to identify the trajectories between consecutive states characterized by the interaction of the injected wave and the nonlinear scatters present in the specimen under study. The analysis of the Recurrence Plots (RP) applied on the state space allows the signal modality characterization: the identification of different signal sources of different signal natures. Measuring the degree of predictability of the resulting signals gives information about how coherent and incoherent components are combined as a function of the inner material and, thus, about the internal damage level of the material.

The study of a deterministic signal has relied on the concept of phase space, which is a vector space that collects all the possible system states that are useful for determining the future evolution of the signal. For a time series \( x(n) \), the phase space would be defined by

\[
\vec{X}_n = [x(n), x(n - \tau), \ldots, x(n - (E - 1) \cdot \tau)]^T, \quad n = 1, \ldots, N - (E - 1) \cdot \tau
\]

where \( N \) is the total number of points, \( \tau \) is the discrete time lag, \( E \) is the embedding dimension [1] and \( T \) refers to the transpose matrix. The proper selection of \( \tau \) and \( E \) is crucial in the further analysis because it affects the correct representation of the data evolution in time. A common approach to determining the value of \( \tau \) is the one proposed by Fraser and Swinney [2] that uses the first null of the time delayed mutual information. The selection of the minimum embedding dimension \( E \) is based on the false nearest neighbour algorithm proposed by Cao [3].

Eckmann et al. [4] introduced a tool called Recurrence Plots (RP) to visualize the recurrence of states which conform the phase space of a signal \( x(n) \). One of the main advantages of the RP is that they allow the \( E \)-dimensional phase-space trajectory, \( \vec{X}_n^2 \), of a signal \( x(n) \) to be investigated through a binary two-dimensional representation of the recurrences of the states. Among the different variations of computing the RP, the most common way is using Equation (2).

\[
R_{n_1, n_2} = \Theta(\varepsilon - ||\vec{X}_{n_1} - \vec{X}_{n_2}||), \quad n_1, n_2 = 1, \ldots, N_s
\]

where \( N_s \) is the number of considered states \( \vec{X}_n \), \( \varepsilon \) is a threshold distance, \( || \cdot || \) is the Euclidean distance, and \( \Theta(\cdot) \) is the Heaviside step function.

A diagonal line in the RP appears when a segment of the trajectory runs parallel to another segment. The length of this diagonal line is determined by the number of consecutive states
for which two trajectory segments have a similar evolution. As a result, the presence of diagonal lines that run parallel to the mean diagonal (line of identity) indicates that the evolution of states is similar at different times and that the process could be deterministic [5]. The percentage of recurrence points that form diagonal lines can be used to measure the degree of determinism (DET). This percentage can be computed as follows:

\[
DET = \frac{\sum_{j=j_{min}}^{N_x} j \cdot P(j)}{\sum_{j=1}^{N_x} j \cdot P(j)}
\]

where \(P(j)\) is the number of diagonal lines of length \(j\) and \(j_{min}\) is the minimum number of points to be considered as a diagonal line (in this work, \(j_{min} = 2\) is used).

III. EXPERIMENTAL

A. Material and Specimens

Eight cubic specimens of concrete (water/cement = 0.65) of 100 \(\times\) 100 \(\times\) 100 mm\(^3\) were manufactured for this experiment. After the iron moulds were filled with the fresh concrete, they were stored in a wet chamber (20°C and 100% RH) for 24 hours. After that, the specimens were removed from the moulds and cured under water at 20°C for 60 days. Four specimens were used to determine the ultimate compressive strength of the material and the remaining four were utilized to perform the ultrasonic NDT analysis. These four remaining specimens were subjected to 0%, 25%, 50%, 75% respectively of their ultimate compressive strength (40 MPa) using a calibrated hydraulic press following the scheme in Figure 1a. Due to the typical inverted-pyramid cracking pattern of a cube specimen under uniaxial load Figure 1b, direct and indirect ultrasonic through-transmission setups were evaluated.

![Diagram](image-url)

Fig. 1: Damage protocol, nomenclature and disposition of the specimens. (1a) Scheme Stress/Strain curve of concrete with the % of load used for this experiment. (1b) Nomenclature of the faces, casting and load direction and cracking pattern.

In Figure 1b, the different faces of a particular cube have been labelled. The two direct ultrasonic configurations were named relatively to the direction of the load. \(A-A\) corresponds to measures acquired in the direction of the load and \(B-B\) corresponds to measures acquired perpendicular to the direction of the load. \(C-C\) configuration could not be measured due to the imperfection of \(C\) (casting face) generated by the manufacturing process of the specimens that leaves a rough face. The four measured indirect configurations have been classified between parallel and perpendicular to the casting planes (Table I).

<table>
<thead>
<tr>
<th>Direct</th>
<th>Indirect</th>
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<tbody>
<tr>
<td>A-A, B-B</td>
<td>A-B, A-B</td>
</tr>
<tr>
<td>A-C, A-C</td>
<td>A-C, A-C</td>
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B. Traditional Ultrasonic Measures

An ultrasonic through-transmission setup was chosen since it offers good penetration and accuracy for the ultrasound measures estimated from the received signal: the p-wave velocity and the attenuation due to the material [6]. For non-continuous waves of a specific frequency, \(f\), propagation velocity (or wavefront speed), \(v_p\) [m/s], is defined as the speed with which the beginning of the disturbance moves. This value equals the phase velocity and the group velocity as long as they are independent of the wavelength (non-dispersive materials).

The computed \(v_p\) is given by Eq. 4,

\[
v_p \ [\text{m/s}] = \frac{d_{mat} \ [\text{m}]}{t_a \ [\text{s}]}
\]

where \(t_a\) [s] is the time that the emitted wave takes to pass through the material (whose distance is \(d_{mat}\) [m]) and it is estimated as the instant of time when the received signal level exceeds 50 % of the noise level.

On the other hand, the examination of the amplitude of the signals at different frequencies revealed interesting features related to the aggregate content and size. The attenuative behaviour of the material implies both, intrinsic (absorption) and extrinsic (scattering) mechanism, which cannot be directly separated. The attenuation coefficient, \(\alpha_{mat}(f)\) [dB/cm], is determined by measuring the reduction of the amplitude of a sinusoidal permanent wave due to the propagation through the material and is given by Eq. 5,

\[
\alpha_{mat}(f) = \frac{P_{tx}(f) \ [\text{dB}] - P_{rx}(f) \ [\text{dB}] - \alpha_{equip}(f) \ [\text{dB}]}{d_{mat} \ [\text{cm}]}
\]

where \(P_{tx}\) [dB] is the transmitted power and can be obtained theoretically from the amplitude of the transmitted signal, \(A_{tx}\), using Eq. (6), \(P_{rx}(f)\) [dB] is the received power and is obtained from Eq. (7) being \(s_{tx}(t)\) the received signal, \(\alpha_{equip}\) [dB] is the attenuation of the equipment and \(d_{mat}\) [cm] is the total length of the specimen.

C. Ultrasonic Layout

The transducers employed for transmission and reception were the KISC from General Electric. Both are broadband transducers which bandwidth is centered at 1 MHz. The
transmitter transducer was excited directly by a programmable signal generator (Agilent 33120A). The received and amplified ultrasonic signal was captured by a digital oscilloscope (Tektronix DPO3014) with a sampling frequency of 50 MHz. And finally, a laptop was used to control the signal generator and to acquire and store the digitized signals by the oscilloscope.

The transmitted signals were different in each performed analysis: a 5 cycles sinusoidal tone burst signal for time of flight estimation and a sinusoidal permanent signal for attenuation and signal modality measurements. The rest of the signal parameters for both cases were: amplitude, $A_{tx} = 10 \text{ V}$, and the fundamental frequency, $f_0$, was swept from 250 kHz to 1.5 MHz in 10 kHz steps (126 measures for each case).

The attenuation associated to the measurement equipment (transducers, amplifier, wires, acquisition module,...), $\alpha_{equip}(f)$, requires a calibration process. The calibration process was carried out facing emitter and receiver transducers without any material between them and, applying the simplified version of Eq. 5 which becomes into Eq. 8 due to the absence of the process of the concrete caused by the cracking process in the loading phase. Propagation velocity extracted from the ultrasonic wave in the different direct configurations for the whole measured frequency range are represented in Figure 2.

The degree of determinism quantifies how the pressure waves combine at their propagation path as a function of the inner heterogeneities, and it must be proportional to the damage suffered by the material. Figure 4 shows the computed degree of determinism of continuous sinusoidal signals for all series and dispositions. Figure 4a shows the determinism curves for direct configuration. It can be observed that determinism curves of 0 % drops at high frequencies (1.4 MHz). 25 % and 50 % performed practically the same behavior, DET drops to 0 values at 1.2-1.3 MHz. 75% series have the highest values of attenuation in all frequencies. 75% series have the highest values of attenuation in the frequency analysis. Figure 3a shows the indirect measures parallel to the rough face, performing quietly the same behaviour in all series and being slightly difficult to distinguish between levels of damage and dispositions.

B. Signal Modality Approach

The degree of determinism quantifies how the pressure waves combine at their propagation path as a function of the inner heterogeneities, and it must be proportional to the damage suffered by the material. Figure 4 shows the computed degree of determinism of continuous sinusoidal signals for all series and dispositions. Figure 4a shows the determinism curves for direct configuration. It can be observed that determinism curves of 0 % drops at high frequencies (1.4 MHz). 25 % and 50 % performed practically the same behavior, DET drops to 0 values at 1.2-1.3 MHz. 75% series drops under 1 MHz. Figure 4b illustrates the determinism curves for the indirect configuration parallel to the casting plane. Notable differences can be identified for each level of load, being the differences between the two dispositions bigger as the load increases. Unlike the attenuation curves, the four determinism curves are easily identifiable. Lastly, Figure 4c shows the determinism curves for the indirect configurations perpendicular to rough face. Despite the attenuation curves were very similar, the determinism curves progressively drop and allow identifying the different levels of load. The differences in determinism between the indirect configurations (Figure 4b and 4c) might be attributed to the manufacturing process of the concrete cubes (wall effect, compaction process, casting direction, etc.), being the signal modality approach the most sensitive characterization measure to distinguish between dispositions and levels of load.
V. C ONCLUSIONS

In this study, a detailed ultrasonic analysis of a concrete cube under uniaxial load has been done. The wave velocity roughly classifies the stiffness of the concrete matrix for direct configurations. The pressure wave propagates in different speed when the direction of the cracks and flaws change. Attenuation measures in a frequency range show interesting information about the defects of the concrete but it does not very clear distinguishing some series depending on the measuring disposition. The degree of determinism accurately characterizes the level of damage even when many echoes are superimposed and/or the wave-front trajectory cannot be accurately estimated. It has demonstrated its ability to classify between dispositions and levels of load. The typical pyramid-cracking pattern and its exhibited asymmetry due to the concrete heterogeneity has been perfectly analysed in terms of determinism when dispositions in indirect configurations were compared.

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