Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Monitoring of compressive stress changes in concrete pillars using cross correlation

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***Abstract*—The use of ultrasound in structural health monitoring of concrete structures is an accepted technique. In recent years more sophisticated signal processing, like coda wave and cross-correlation of signals have been used. In this paper, we investigate different signal processing techniques of the coda wave signals in order to analyze the compression of a concrete pillar. Four metrics were compared, namely, the energy of the signal, the maximum of the correlation function, the time of correlation maximum and the symmetry around the maximum. Results are presented for different temporal windows.**

Keywords—structural health, cross correlation, coda waves.

I. INTRODUCTION

The use of ultrasound in structural health monitoring of concrete structures is an accepted technique [1-3]. The use of the ultrasonic speed of both S and P waves gives structural information and a simple interpretation. However, in recent years more sophisticated signal processing, like coda wave and cross-correlation of signals have been used [4,5]. These techniques are highly sensitive to small changes in the structure's behavior. These changes are not absolute but only relative measurements from a reference state. The use of coda waves to evaluate the state of rocks and aggregate material has been used for many years, especially in geophysics and material science [6]. More recently, several authors addressed the problem of the determination of the load state in a concrete pillar or in a concrete structure using coda waves [7-10].

Coda waves, or multiple scattering waves, have a lot of information about the propagation path because it involves several propagation modes, reflections, scattering, etc. On the other hand, these wave-modes are also sensitive to external factors that disturb the media, for example, temperature changes [11]. When a signal containing multiple reflections is to be analyzed, it is necessary to determine the time window, the frequency range and the signal processing to be applied in order to analyze the effect of external factors in the signal.

In this paper, relative changes of a concrete pillar are monitored for different load states using cross-correlation with a reference state. The objective is to compare the results of applying different signal processing techniques/features to monitor the stress state. Four techniques/features were selected, namely, first, the difference between the signals' total energy, second, the relative changes between the cross-correlation maximum values, third, the time differences in which the maximum values occur, and fourth, the symmetry differences between the correlation maxima.

II. EXPERIMENTAL SETUP

The experiment comprised one prismatic specimen of 15 x 15 x 60 cm³, cast from a concrete batch of compressive strength of 34.6 MPa and density 2146 kg/m³. Table 1 contains the concrete mixture design.

TABLE I. CONCRETE MIXTURE DESIGN, CONSTITUENT WEIGHS PER M^3 OF CONCRETE.

	Weight Batches (kg)
Cement	380
Fine gravel	1100
Coarse sand	367
Fine sand	367
Water	161

The prism was subjected to several loading/unloading cycles in steps of approximately 1 MPa, ranging from 0 to 6 MPa, in uniaxial compression. The compression was applied onto the prisms using an electro-mechanical automatic testing machine brand Controls. The load was applied/removed at a rate of 200 N/s. At each loading step, the compression was kept constant for approximately 18 minutes. The loading/unloading protocol is depicted in Figure 1.

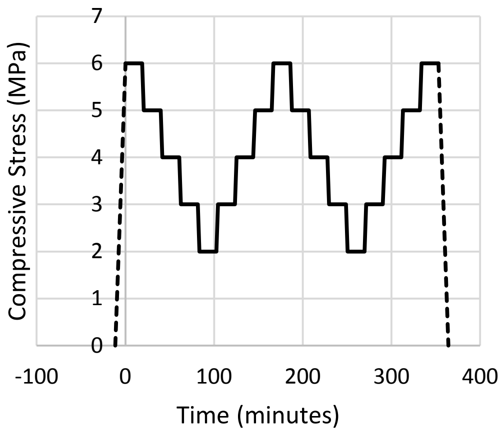

Fig. 1. Loading/unloading protocol showing the level of applied compression as a function of time. Ultrasound tests were carried out during loading steps marked with continuous black lines.

Two pairs of shear transducers Olympus V1548 were attached to opposing sides of the specimen as shown in Figure 2, one transducer set as emitter and the other one as receiver. An Olympus 5072PR pulser-receiver was conditioned to excite one emitter at a time and to collect the response that reaches its corresponding receiver. A pair of transducers was positioned to work with vertically polarized shear waves (SV), whose polarization was set parallel to the uniaxial stress, whereas the other pair worked with horizontally polarized shear waves (SH), perpendicular to the uniaxial stress. Analog signals were digitized with a Tektronix oscilloscope model TDS2004B and then processed with a personal computer.

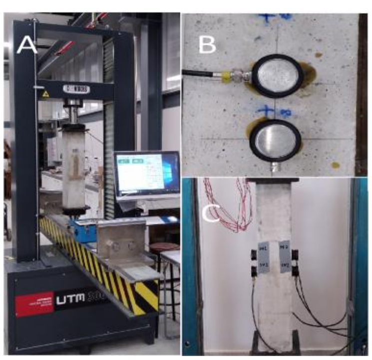

Fig. 2. Experimental setup. A) Electro-mechanical testing machine, B) ultrasonic transducers, C) Pliar placed in the machine with the ultrasonic assembling.

III. SIGNAL ACQUISITION

During the tests, transmission signals were acquired every 30 seconds. The time-window for signal acquisition was 3 ms using a sampling frequency of 500 kHz. Due to material attenuation, high frequencies are strongly attenuated. This effect can be observed both in time and frequency domains, as shown in Figure 3.

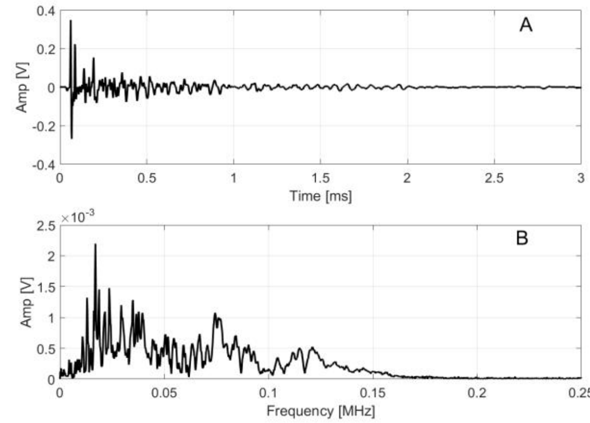

Fig. 3. Signals acquired in transmission mode. A) raw signal, B) Fourier spectrum.

IV. SIGNAL PROCESSING

A. Energy

The simplest processing to apply in this case is the computation of the signal energy. This computation can be carried out in the time domain as:

$$E = \sum_{n=i}^{i+N-1} y^2\,(t_i) \tag{1}$$

where N is the total number of samples of the acquired signal $y(t)$. Also, the temporal window (t_i to t_f) can be arbitrarily defined. Note that, prior to calculating (1), the mean value is subtracted from $y(t)$.

B. Cross-correlation amplitude

The cross-correlation function is computed in the frequency domain as

$$C_{1,2} = \Im^{-1}(Y_1 Y_2^*). \tag{2}$$

In this case, $C_{1,2}$ is the correlation between two different signals acquired under different conditions and Y is the Fourier transform, $\Im\{y(t)\}$, of the signal y. This correlation function has a well-defined maximum. For small differences between two signals, the amplitude of the cross-correlation maximum indicates the degree of correlation between both signals. This maximum can be used as a measure of changes in the propagation media.

C. Cross-correlation time

The maximum of $C_{1,2}$ can also present a delay in time. This delay is produced by changes in the phase of the spectrum components. The changes in the time of correlation maximum can be also used to measure the changes in the propagation media.

D. Cross-correlation symmetry

The autocorrelation function is symmetric around its maximum. Depending on the phase and amplitude difference between the signals, the symmetry with respect to the maximum could be lost. As a measure of symmetry loss, the absolute difference between the first minimum value after and before the maximum is used. Note that the autocorrelation functions have a well-defined minimum after and before its maximum.

V. EXPERIMENTAL RESULTS

In this section, we present the experimental results using a unique set of signals, which were acquired in a single experiment. The same raw signals were processed independently by using the four proposed techniques. For all four techniques, the processing was carried out using three time-windows, namely, the entire extent of the signal (i.e., no windowing) a temporal window for times $t < 1$ ms and another one for times $t > 1$ ms.

A. Energy

Energy results were normalized by the energy of the first signal. These results are shown in Figure 4.

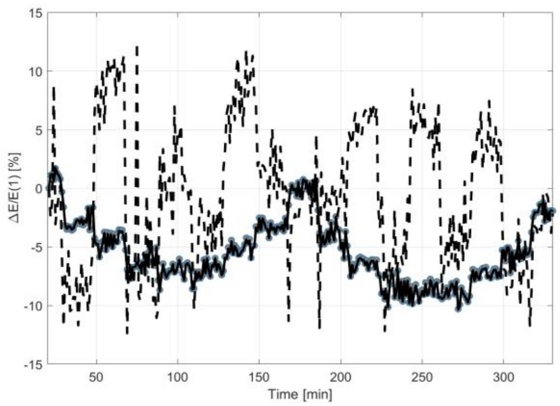

Fig. 4. Results for Energy signal processing. Continuous black line is the full signal time-window, dotted gray corresponds to the time-window t,<1 ms, dashed black line to time-window t> 1 ms.

B. Cross correlation amplitude

Cross correlation results were normalized by the autocorrelation maximum of the first signal. These are shown in Figure 5.

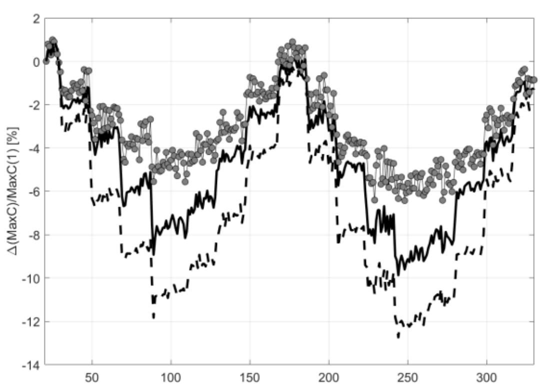

Fig. 5. Results for cross correlation amplitude signal processing. Continuous black line is the full signal time-window, dotted gray corresponds to the time-window t,<1 ms, dashed black line to time-window t> 1 ms.

C. Cross correlation time

Cross correlation time results were normalized by the half temporal window. These are shown in Figure 6. We shifted the time-vector to place the maximum of the autocorrelation function at the center of the temporal window.

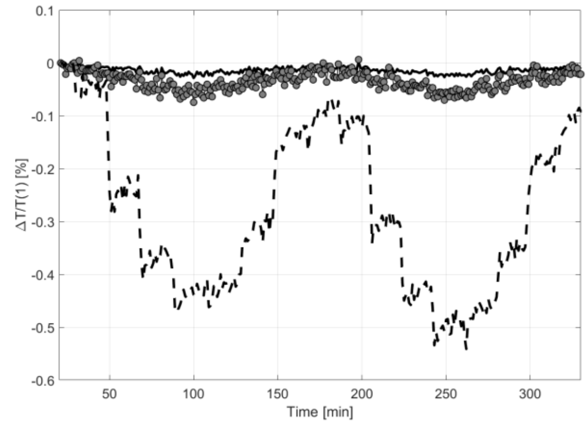

Fig. 6. Results for cross correlation time signal processing. Continuous black line is the full signal time-window, dotted gray corresponds to the time-window t,<1 ms, dashed black line to time-window t> 1 ms.

D. Cross correlation symmetry

Cross correlation symmetry results were normalized by the mean value of the minimum of the autocorrelation function. These are shown in Figure 7.

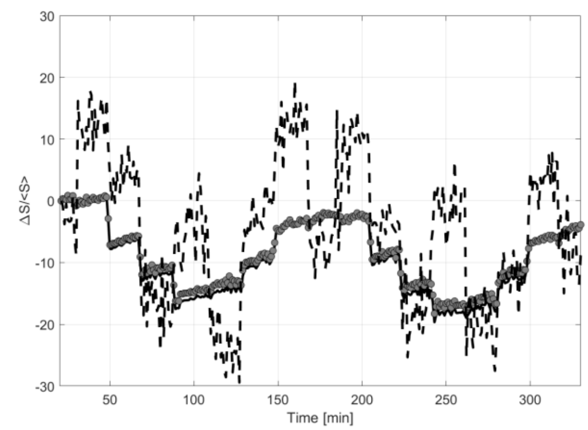

Fig. 7. Results for cross correlation symmetry signal processing. Continuous black line is the full signal time-window, dotted gray corresponds to the time-window t,<1 ms, dashed black line to time-window t> 1 ms.

VI. DISCUSSION

The use of the multiple scattering waves between a pair of transducers can be used to monitor the load state of concrete specimens. This technique has been successfully applied by several authors [7-10]. The usual signal processing is the study of the cross-correlation function between a reference state and the actual state. Here we analyze, for this particular application, the effect of different types of techniques/features to extract information from the correlation function.

The four studied techniques are sensitive to relative changes in the stress state of the specimen. However, the use of the three different time-windows has a direct impact on the results. The time window t<1 ms contains the ballistic pulse and dominates the energy of the signal. Also, it contains high-frequency components which are attenuated for longer propagation times. On the other hand, the time-window t>2 ms contains mostly the information of multiple scattering reflections within the specimen. In Figure 4, we observe the expected result where the energy of the signal is dominated by the first times. However, in this case, the energy for the t>2 ms window seems to be highly sensitive but it does not reproduce the load pattern of Figure 1. If we were to use this signal processing technique it would be better to acquire a shorter signal. Note that this technique involves the simplest processing.

Considering the results for the maximum of the correlation function, see Figure 5, we observe the opposite result. The best results are yielded by the time-window t>2 ms. Even though the maximum of cross-correlation depends on the energy, it is strongly influenced by the phase of the frequency components. Then, in this case, it is better to use a temporal window avoiding the ballistic pulse.

In the case of the time in the maximum correlation function, see Figure 6, again the best results correspond to those yielded by applying the t> 2ms time-window, where the multiple scattering occurs. This time is highly dependent on changes of the phase in the spectrum components showing good consistency with the results in the amplitude of correlation.

In the case of the cross-correlation symmetry, see Figure 7, we see again high sensitivity of the multiple scattering. In this case, the information does not reproduce the load pattern and it would be better to use a shorter temporal window.

In all experiments, an overall drift can be observed. This is produced by changes in the temperature of the room by 3.5 ^{o}C from the start to the end of the experiment. These changes can be compensated by using a dummy pillar. For the sake of brevity, the results of the compensation are not included in this first paper.

Additionally, a study about the frequency band used to process the signals can be made. We observe relative parallelism between the use of lower frequencies and the use of the multiple scattering signal. This is due to the filter introduced by the attenuation. Results analyzing the effect of the frequency band are not included here.

VII. CONCLUSION

This is a first study that discusses the use of several features extracted from the cross-correlation function of multiple scattering signals in order to monitor the stress state in concrete pillars. The application of a particular signal-processing to obtain the load state in a pillar strongly depends on the temporal window and the frequency band selected. The selection is not obvious, and it depends on the particular technique being used. The reason for these results can be understood better in the frequency domain. The global signal is composed of the sum of all components of the frequency spectrum. Each component travels through the structure by different paths changing its amplitude and phase. The result of the sum can be constructive or destructive depending on the propagation of the different modes. Thus, each problem must be analyzed in particular.

ACKNOWLEDGMENT

The authors wish to thank to Brazilian agency CNPq for the partial financial support to this work. Also, the authors wish to thank the Uruguayan agencies ANII and CSIC-UdelaR for the support in the actual research line.

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