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Detection of rebars in concrete using advanced ultrasonic pulse compression techniques

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ABSTRACT

A pulse compression technique has been developed for the non-destructive testing of concrete samples. Scattering of signals from aggregate has historically been a problem in such measurements. Here, it is shown that a combination of piezocomposite transducers, pulse compression and post processing can lead to good images of a reinforcement bar at a cover depth of 55 mm. This has been achieved using a combination of wide bandwidth operation over the 150–450 kHz range, and processing based on measuring the cumulative energy scattered back to the receiver. Results are presented in the form of images of a 20 mm rebar embedded within a sample containing 10 mm aggregate.

1. Introduction

Non-Destructive Testing (NDT) using ultrasound is a well-established method for monitoring concrete structures [1–4]. Ultrasonic NDT (UNDT) has found wide application to concrete in, for example, determining the water-to-concrete ratio [5–8], monitoring of hardening [9,10] and strength [11], detecting damage [12–17] and investigating the condition of reinforcement bars (rebars) [18–21]. Even though the technique has become part of many national standards for concrete diagnostics [22], several of its possible applications are still very challenging and many others are under development. They include the presence of damage, cracks, failures or the integrity of reinforcement bars, when only one side of the structure under-test is available for the inspection.

The ultrasonic NDT of concrete can be achieved in several different configurations. A single ultrasonic transducer acting as both a transmitter (T_x) and a receiver (R_x) can operate in the pulse-echo configuration. Alternatively, a pair of transducers arranged either in through-transmission or in pitch-catch modes, as depicted in Fig. 1(a) and (b) respectively.

In both cases, the T_x is normally driven by a delta-like pulse voltage signal, which excites the natural resonance frequency of the transducer. The ultrasonic wave packet is then recorded from the R_x after its path into the concrete. The features of interest are retrieved by measuring the time taken by the ultrasonic wave to travel from the T_x to the R_x, i.e. Time-of-Flight (ToF) measurements [23,24], or by evaluating the attenuation of the received signal amplitude after its path into the concrete sample [25–27]. In such inspections, cracks, voids but also any functional inclusions such as aggregates or rebars embedded within the concrete act as scatterers for the impinging ultrasonic wave, resulting in a complicated interpretation of echograms. In addition, the presence of aggregates of various dimensions makes concrete highly attenuating towards the acoustic excitation sent, thus limiting the maximum depth of inspection and leading to a poor Signal-to-Noise Ratio (SNR) [28]. It is worth noting that both the attenuation and the scattering magnitude are frequency-dependent, and that they increase if high excitation frequencies are used for concrete ultrasonic inspection [29,30]. For the sake of the SNR enhancement, narrow-bandwidth piezoelectric transducers are usually used, which tend to resonate within a narrow frequency range (typically 50–70 kHz and excited with a high-voltage pulse). This is to generate a high energy signal to be delivered into the sample. However, the use of narrow-band transduction systems limits (i) the spatial range resolution, (ii) the lateral resolution and (iii) the features that can be extrapolated from the frequency domain analysis [31,32].

Recently, the use of a coded waveforms such as chirps, together with the Pulse Compression (PuC) technique, has been proven to be

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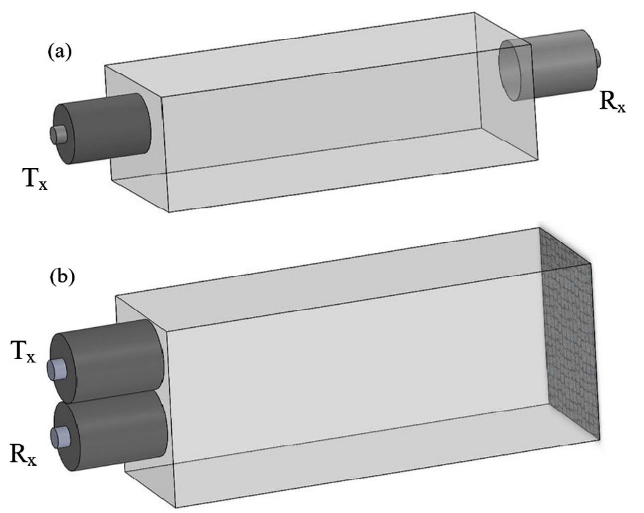

Fig. 1. (a) Through-transmission and (b) pitch-catch transducer inspection arrangement.

a powerful tool for inspecting highly attenuating materials [39,40]. This is because the SNR can be enhanced almost arbitrarily by simply increasing the time duration of the excitation without affecting the signal bandwidth [41]. The use of coded waveforms and PuC for UNDT in concrete quality assessment has already been reported, either by using transducers in contact with the concrete structure [42–44] or by utilizing air as a coupling medium [32,45]. Furthermore, recent progresses on material research and transducers manufacturing process have led to the fabrication of contact transducers capable of providing longitudinal ultrasonic wave within a broad-band frequency range. PuC thus has the potential to increase the SNR and the imaging capabilities in concrete inspection, especially in term of spatial resolution. However, there is still a need to improve the capability of discriminating between "true" defects and artefacts produced by an erroneous processing of the acquired data. One example is the detection of a true scattering object or defect in the presence of strong back-scatter from aggregate.

In this work, PuC and an original imaging procedure will be used to accomplish the above goal, using (i) a pair of broad-bandwidth piezocomposite transducers to excite the concrete sample under test by longitudinal ultrasonic wave arranged in pitch-catch configuration, and (ii) a low-voltage chirp signal excitation over a frequency range of 150–450 kHz. This combination acts so as to both counterbalance the attenuation and to increase the lateral resolution with respect to standard concrete testing methods. The extended bandwidth is one of the key characteristics that allows pulse compression to be used. It is also worth noting that a pitch-catch configuration was used, as shown in Fig. 1(b). This choice was made to allow extended excitation waveforms, in the form of swept-frequency chirp signals, to be used (these would normally be a problem with pulse-echo measurements, as the drive waveform would mask many received signals from within the sample).

It is also necessary to consider the data analysis which best allows the detection of inclusions, flaws, cracks, voids, reinforcement bars, etc. within a real concrete sample. Typically, an ultrasonic NDT test would be performed as a B-scan or C-scan, and the peak-to-peak amplitude of the back-propagating signal recorded at each scanned position. Increasingly, imaging procedures capable of improving the spatial resolution by fusing the information from many measurements have been used, such as the Synthetic Aperture Focusing Technique (SAFT) [33,34]. Arrays of ultrasonic transducers can be used in these cases to both speed up the data acquisition and to allow ultrasonic beam shaping via a phased array. As an example, the combination of SAFT and array of ultrasonic transducers at low frequency has been used successfully for imaging back walls, internal layers and reinforcement bars embedded within concrete structures [35–38]. SAFT increases spatial resolution in comparison to standard B-scans or C-scans, and can help to reduce artefacts but it has some drawbacks, the main one being the computational time required. In addition, it does not easily allow an increase in discrimination between defects and backscatter from "natural" inhomogeneities such as aggregate; hence it does not automatically detect the main anomalies present in the structure under such conditions.

Here, an innovative imaging technique is presented capable of identifying the major sources of scattering while significantly reducing the computation time. The technique is based on the extraction and visualization of some features from the cumulative values of the energy reflected back to the receiver. The resultant imaging capability has been tested on the data obtained by scanning across the surface of a concrete sample containing a reinforcement bar (rebar) buried within it. The images obtained have then been compared to standard C-scan images.

2. Theoretical background

The reader is referred to other publications [41,43,46] for an in-depth description of PuC basic theory and details of coded signals and design procedures. Here, the limitations arising from using either delta-like excitations and/or narrow-band piezoelectric transductions systems can be highlighted by introducing the concepts of a Linear-Time Invariant (LTI) system and an impulse response. This will help the reader to understand the advantages of using a broad-bandwidth transducer and coded signals, here in the form of linear chirp signals, together with the PuC technique.

2.1. LTI systems and impulse response

The behaviour of any LTI system is univocally described by its impulse response $h(t)$, which is the time-domain response of such a system when excited by a delta-like input signal $\delta(t)$, as shown in Fig. 2. In a real UNDT for concrete inspection, the $\delta(t)$ voltage driving the T_x is sufficiently low to avoid the onset of non-linear phenomena within the concrete structure under test or in the measurement apparatus, thus allowing the inspected volume to be modelled as an LTI system. Under this hypothesis, the features of interest in any ultrasonic NDT measurement can be extrapolated by analysing the time/frequency behaviour of the measured $h(t)$. Ideally, driving an LTI system by a $\delta(t)$ input signal corresponds to exciting the system under test across the whole frequency spectrum with a flat constant amplitude. However, the limited bandwidth of any real transduction system acts as band-pass filter for $\delta(t)$, thus limiting the frequency range into which the LTI system is effectively excited. Therefore, only an estimate $\hat{h}(t)$ of the $h(t)$ can be retrieved, whose quality directly depends on the available frequency bandwidth B and whose magnitude is related to the physical attenuation given by any medium into which the acoustic energy propagates before being recorded. Therefore, the peak-to-peak amplitude of $\delta(t)$ should be increased to provide a high SNR. However, driving voltage cannot be enhanced arbitrarily. This is because both safety rules in several industrial environments and physical limits of the transductions systems restrict the maximum applicable driving voltage.

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