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Amplitude and phase measurements of continuous diffuse fields for structural health monitoring of concrete structures

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A R T I C L E I N F O

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Measuring amplitude and phase of continuous ultrasonic waves with a lock-in amplifier is shown to give similarly sensitive indicators of concrete damage as pulsed coda wave analysis, but maintains its sensitivity at considerably much lower signal levels. Continuous and pulsed measurements were performed on a concrete slab subjected to cyclically increased damage level. In the unloaded phase each measurement type was performed at varying transmit signal levels. The result indicates the possibility of using a larger distance between transducers in high frequency health monitoring systems of concrete structures, where attenuation of propagating waves is strong.

1. Introduction

There is an increasing demand on the reliability and safety of civil structures as these are growing in numbers and getting older. In general, early warnings of degradation or damage is desired, without invasive test procedures. For this reason, much effort has been put into developing the fields of non-destructive testing (NDT) and structural health monitoring (SHM).

Ultrasonic waves, with a variety of methods, have been successfully used in NDT of concrete structures [1,2]. Measuring velocity, attenuation and nonlinearity of propagating ultrasonic pulses have been shown to give indicators of cracking, with increasing sensitivity in the order mentioned [3–5]. Methods based on guided-waves commonly involve only analysis of the direct propagating wave, and thus only investigate the direct path between two sensors. This is not optimal in SHM of large civil structures where it is necessary to monitor as large a volume as possible, with the fixed sensor locations. One method which addresses this issue is to transmit a signal and measure the diffuse field created by boundary reflections and waves scattered by the heterogeneities in the concrete. By analyzing these trailing parts of the measured signal (coda waves), a larger volume is probed. Although it is, by definition, not possible to attribute features in the diffuse signal to any one specific bulk or guided wave mode, it has been shown that they are very sensitive to material changes [6–9]. This sensitivity can be attributed to the fact that the trailing parts of the measured signal correspond to waves which have traversed a relatively large volume and has thus been more affected by change in the material than the parts corresponding to the direct propagation path.

A major challenge in using the diffuse field is its sensitivity to changes in transducer location and coupling conditions between measurements. This issue is largely circumvented in SHM since the transducers are permanently fixed to the structure. Piezoceramic transducers (PZT) are commonly used, either embedded into the concrete or mounted on the surface. These are used both as transmitters and receivers of the mechanical waves and thus provide an efficient solution for SHM applications. In contrast, hammer impact hits, although generating strong pulses which can travel relatively far, are not suitable for SHM applications since they are not perfectly reproducible and cannot be used for reciprocal transmission and reception.

The implementation of coda wave analysis in both NDT and SHM applications and the ability of the method to detect early onsets of cracking in concrete have been extensively investigated [10–14]. There exist different methods for analyzing coda waves, including the doublet method [7–9] and the stretching method [6,15,16] among which the latter of these has been shown to be more precise and more stable towards noise [17].

Coda wave analysis has been used to follow other changes to concrete than cracking; thermal damage to the material is shown in [13] and velocity variations in the medium due to stress (acoustoelastic effect) can be followed clearly in e.g. [18,19]. In these works it is also shown that coda wave analysis is very

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sensitive to temperature variations, and some bias control technique is necessary to increase resolution and avoid false indications of damage. Further temperature bias control techniques are presented in [20]. Measuring the acoustoelastic effect yields information on nonlinear characteristics of the probed structure, which is known to be sensitive to microscopic damage. Recent research [21,22] shows alternative methods for detecting such nonlinearities with coda waves. In these studies low frequency "pump" acoustic signals are input to the structure while high frequency coda wave analysis is performed. Due to microcracking in the concrete, providing nonlinearity, the high frequency coda wave signals are modulated with the low frequency pump signals. By using different amplitudes of the pump signal and investigating the effect on the high frequency signal a measure of the nonlinear behavior of the material is yielded. Such measurements are shown to be more sensitive to microcracks, than linear parameter measurements, and less sensitive to temperature variations.

One issue with coda wave analysis, and guided waves in general, in civil structures is the fact that the attenuation of mechanical waves is substantial in concrete. This makes covering large areas difficult as the transducers have to be placed at close distance. For this reason, the prospect of being able to detect weaker signals, and thus increase transmission range, is appealing.

One method of achieving this is to use single frequency tones as excitation, as opposed to transient bursts. If a single frequency is transmitted continuously a steady-state diffuse field will stabilize after a short period of time, consisting of direct propagation, reflections in boundaries and scattered waves. The signal measured at any receiver location will then be a superposition of all different propagation paths between actuator and receiver. This removes any temporal information in the measured signal, which impedes spatial resolution. However, an advantage is the increase in energy of the scattered and reflected waves, which otherwise rapidly attenuate below the noise floor. Furthermore, continuous signals can be detected at low amplitudes, even well below the noise floor. This gives potential to increase the distance between transducers and thus enabling monitoring of larger structures.

In published work by Yan et al. [23], Liao et al. [24] and Song et al. [25] continuous waves were used in SHM of concrete beams subjected to damage. The frequency of the continuous transmission was swept over an interval and the energy at different frequency bands was calculated using wavelet package decomposition. Damage to the concrete was correlated with a decrease in energy.

Weaver et al. have presented interesting work, where devices are described and demonstrated which output high energy ultrasonic signals with extremely narrow band-widths. These can be regarded as ultrasonic analogues to optical lasers. Different systems are described, e.g. one where a piezoelectric transducer is part of a nonlinear electronic circuit which will oscillate with a certain frequency [26]. It was shown that an externally applied acoustic wave field can stimulate coherent acoustic emissions from the oscillator, with the same frequency as the external waves, as long as this frequency is close to that of the self-oscillations of the circuit. Several such oscillators can lock in to each other leading to a net increase in energy in a coherent, narrow-band signal. In other work, the authors describe systems where the input of a transmitter is connected to the output of a receiving transducer, in a feed-back loop [27,28]. The result is a narrow-band signal, whose frequency depend on the properties of the propagation medium. Such a system can be used for monitoring changes to a structure, with high sensitivity. These techniques are not implemented in this study, but are of interest in applications where single-frequency measurements are performed, as they have potential to increase transmission efficiency.

Although studies exist where continuous transmission have been used for SHM purposes, to the authors' knowledge, there is no comprehensive comparison of pulsed and continuous transmission for SHM applications. The presented study therefore investigates the use of straightforward amplitude and phase measurements from single-frequency continuous acoustic transmissions as indicators of damage and compares the sensitivity to pulsed coda wave analysis. The measurements of the continuous signals were performed with a lock-in amplifier, which is known to be able to detect very low signal levels. In order to simulate increased transducer distance, the amplitudes of the transmitted signals were gradually reduced.

2. Materials and equipment

2.1. Concrete sample

The tests were conducted on a concrete slab with dimensions $1.2 \times 0.8 \times 0.15$ m^3 and a water-cement-ratio of 0.45. The material composition of the concrete is given in Table 1. The slab was reinforced with a steel mesh (nominal diameter = 6 mm) in the tension face, with 6 reinforcement bars in the direction of the strain and 7 perpendicular. Fig. 1 shows the layout of the reinforcement. The slab was cured in room temperature for 31 days, sealed with plastic sheets, before the testing.

2.2. Ultrasonic transducers

Piezo ceramic discs (Ferroperm Pz 27) with diameter 38 mm and thickness 10 mm were used as ultrasonic transducers. The discs were glued to 25-mm-high aluminum cylinders. BNC connectors were installed into threaded holes in the cylinders and connected to either pole of the ceramic discs. The transducers, PZT disc and aluminum cylinder combined, have a major resonant frequency at 47 kHz.

2.3. Pulsed transmission

For the transient measurements, an Agilent 33500B Waveform Generator was used to output a 5-cycle, Hanning-windowed, sinusoidal pulse with a center frequency of 47 kHz as excitation of the transmitter. Fig. 2 shows the excitation pulse in time and frequency domain. The signals measured by the receiver were put through a Krohn-Hite 3905B Multichannel Filter set to high-pass, with a 5 kHz cut-off frequency, and a gain of 20 dB. The filtered and amplified signal was sampled with an Agilent InfiniiVision DSO-X 3014A oscilloscope.

2.4. Continuous transmission

For the continuous measurements, the transmitter was excited by a continuous sinusoidal wave of frequency 47 kHz, generated by the 33500B waveform generator. The signal was left on for 300 ms

Table 1
Composition of concrete.

Components	Values (kg/m^{3})
Cement	400
Fine aggregate (0–8 mm)	890
Coarse aggregate (8–11 mm)	445
Coarse aggregate (11–16 mm)	445
Water	180
Superplasticizer (polycarboxylate, Sikament EVO 26)	0.83