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Fröjd, Patrik; Ulriksen, Peter

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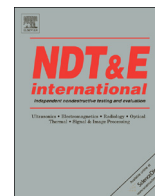
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PO Box 117
221 00 Lund
+46 46-222 00 00



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



P. Fröjd*, P. Ulriksen

Department of Engineering Geology, Lund University, John Ericssons väg 1, 221 00, Lund, Sweden

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ABSTRACT

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.

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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

* Corresponding author: Tel.: +46 46 222 89 83.
E-mail address: patrik.frojd@tg.lth.se (P. Fröjd).

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 $1.2 \times 0.8 \times 0.15 \text{ m}^3$ 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 (Ferropem 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

before any measurements were made, providing sufficient time for the development of a steady state.

The signals from the receiving transducer were put through the Krohn-Hite filter, with the same settings as for the pulse transmissions, and sampled with a Signal Recovery 7210 Multi-channel Lock-In Amplifier. The lock-in amplifier outputs the amplitude of the measured signal and its phase, relative to the driver signal (provided by the signal generator).

3. Acoustical measurements

3.1. Measurement procedure

The concrete slab was instrumented with the two PZT transducers on the tension face, 700 mm apart and centered on the slab. The transducer to the right of the center acted as actuator and the one to the left as receiver. The transducer locations are displayed in Fig. 1.

The slab was placed with supports 100 mm from the edges. Using a hydraulic testing machine, the load was applied as a line along the width of the slab so as to create cracks centered between transmitter and receiver. The loading protocol used was to apply an increasing load in steps, release the load between steps and then perform the acoustic measurements. Thus, the measurements were performed on an unloaded slab and developed cracks were, at least partially, closed. Each load level was chosen to be 2 kN greater than the previous one. A load cell in the testing machine measured the applied load and a displacement transducer measured the deflection of the slab.

Directly after the release of each load step, both transient and continuous transmission acoustic measurements were performed at different voltage levels of the driving signal, ranging from 10 V to 1 mV. This was made in order to simulate an increased distance between the transducers, by decreasing signal-to-noise ratio, and investigate the lower limit for where the two methods can detect damage. At each voltage level, 20 pulsed transmission measurements were performed in order to enable averaging.

The choice of 47 kHz signals gives a shear wave wavelength of ~4 cm, which is slightly larger than the largest aggregates in the concrete. This means that the transmissions were in the simple scattering regime [12]. The coda thus consists of some scattered waves, but mostly of reflections in the boundaries. The number of reflections, and their amplitude at the receiver position, depend on the geometry of the concrete slab. With the specimen dimensions and transducer placement used in the presented study, many reflections in the boundaries were measured with the same order of magnitude as the direct propagation wave.

Coda wave analysis is often performed with higher frequency signals, which are more sensitive to changes but are more quickly attenuated in the material. Like in all ultrasonic measurements, there is a trade-off between range and resolution or sensitivity, and since the aim of the study is to investigate the use of diffuse field measurements in large structures a relatively low frequency was chosen.

The signal frequency was chosen since it was the resonance frequency of the transducers. The frequency is much higher than the major resonant frequencies of the concrete specimen, and the characteristics of the transducers are assumed to influence the transmissions more than the modes of the slab.

3.2. Data processing

For both modes of transmission, damage was estimated by analyzing attenuation and velocity change as the concrete slab is damaged. For the pulsed transmission, this was done with the

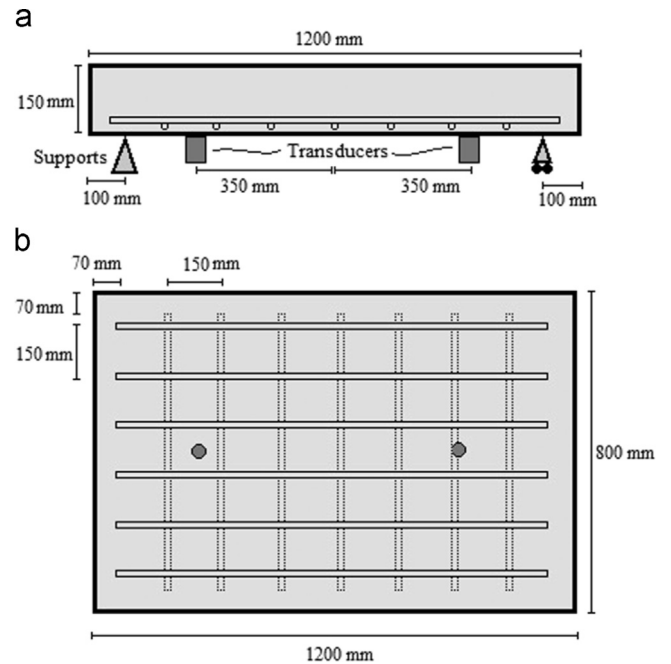


Fig. 1. Concrete dimensions, reinforcement layout and transducer locations. Concrete slab seen from the side (a) and from above (b).

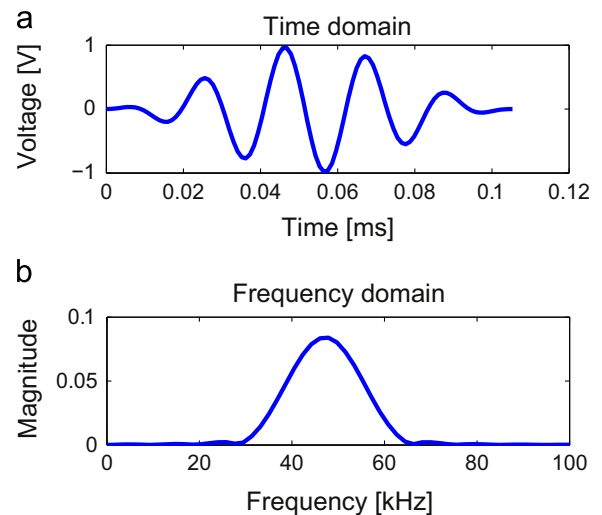


Fig. 2. Excitation signal for pulse measurements in time (upper) and frequency (lower) domain.

energy dissipation method [29] and the stretching method [6,15,16]. Before evaluation of damage the measured pulses were averaged over the 20 samples and passed through a digital 5-pole Butterworth band-pass filter with cut-off frequencies at 30 and 70 kHz in order to suppress noise. In the frequency range of interest, the noise was approximately white.

For the energy dissipation evaluations, the energy content of each measured waveform was calculated with

$$E = \sum_{k=1}^N \left[\frac{1}{2} (A_k + A_{k+1}) \right]^2 \cdot \Delta t$$

where A_k is the amplitude of the signal at sample k , Δt is the time step and N is the number of samples. The energy measured for pulses transmitted through the undamaged sample was used as baseline. The dissipated energy for each state of damage was

defined as the ratio between the current pulse energy and the baseline energy.

The stretching method was used to estimate the variation of velocity between two diffuse ultrasonic pulse signals. The baseline coda signal was interpolated at times $t(1+\alpha)$ in a time window $[t_1, t_2]$. This corresponds to a stretching or compression of the reference signal which was then compared to the measurement signal from the possibly damaged structure by computing the correlation coefficient:

$$CC(\alpha_i) = \frac{\int_{t_1}^{t_2} u_r(t(1+\alpha_i))u_d(t)dt}{\sqrt{\int_{t_1}^{t_2} u_r^2(t(1+\alpha_i))dt \int_{t_1}^{t_2} u_d^2(t)dt}}$$

where u_r and u_d are the reference signal and the signal from the damaged structure respectively and α_i are different stretching factors. The α that maximizes the correlation coefficient is equal to the relative modification of the propagation velocity.

For each continuous measurement, only two scalar values were acquired; amplitude and phase, relative to the exciting signal. According to the manufacturer, the dynamic reserve of the lock-in amplifier is better than 80 dB i.e. 10^{-4} and the phase accuracy is 2° .

Attenuation was evaluated as the ratio between each measured amplitude and that of the baseline signal. Changes in phase give an indication of change in velocity in the medium. Since the measured phase is that of the scattered wave field the velocity change is an average of all propagation paths between the transducers.

Measurements were performed at different levels of transmission signal amplitude. The signal-to-noise ratio (SNR) was evaluated at each transmission level according to

$$SNR = 10 \cdot \log_{10} \left(\frac{A_{sig}}{A_{noise}} \right)^2$$

where A_{sig} is the amplitude of the highest peak in the pulse, measured on the undamaged concrete slab and A_{noise} is the root-mean-square of the white noise in the measured signal, after band-pass filtering.

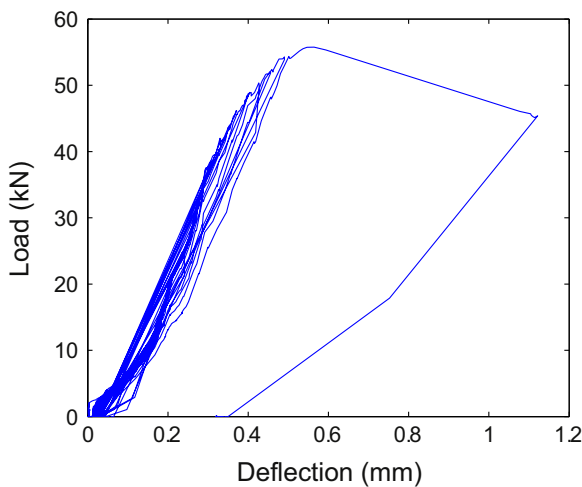


Fig. 3. Response of the concrete to the loading procedure. The reinforcement bars yielded at ~ 57 kN load. Acoustical measurements were performed while the slab was not loaded.

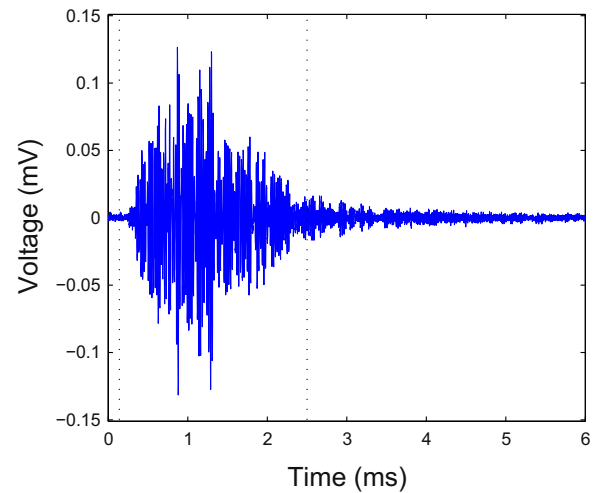


Fig. 4. Averaged and filtered pulse measurement. Vertical, dotted lines show time window used in the coda wave analysis.

4. Results and discussion

In order to induce damage in the material, the concrete slab was loaded and unloaded according to the cyclic loading procedure. The applied load was increased until the reinforcement bars yielded. After this, an applied load could not be maintained at a constant level.

Fig. 3 shows the response of the beam during the loading procedure. The reinforcement bars yielded at ~ 57 kN load. Cracks were only visible on the surface of the concrete just before yielding of the reinforcement bars. After unloading of each load step, both continuous and pulse measurements were performed. **Fig. 4** shows the average of 20 measured pulses, filtered with a digital band-pass filter. It can be seen that multiple reflections are recorded and mixed, which support the claim that the waveform is diffuse. A 3D estimation, using the equivalent spherical volume, yields an average of ~ 11 reflections, assuming a velocity of 2600 m/s for a window of 2.5 ms. A similar method of estimating the number of reflections is used in e.g. [30].

It is known that the late part of the coda is more sensitive since this part corresponds to waves reflected more times than the earlier parts. However, it was observed that this part was obscured at low SNR, and since a consistent reference was desired for all SNR levels, the parts of the signal with high amplitude was used. The time window used is visualized in **Fig. 4**.

4.1. Energy/amplitude measurements

After each unloading of the concrete slab, new acoustical measurements were performed, and the amplitude of the continuous signals and the energy content of the pulses were measured. These are shown in **Fig. 5** as a function of the concrete deflection during the preceding load step. The values are normalized with regard to the first measured energy/amplitude. Each sub-figure shows the amplitude and energy ratio for decreasing transmission signal levels. The uppermost left sub-figure shows data from measurements with a high signal-to-noise ratio. It can clearly be seen that the transmitted signal is increasingly attenuated as the concrete is loaded. The continuous and pulse transmissions show very similar sensitivity to the damage.

However, as the transmission signal level is decreased the pulse measurements become less coherent, and show little or no relation to the level of damage in the concrete. It is clear that the pulse

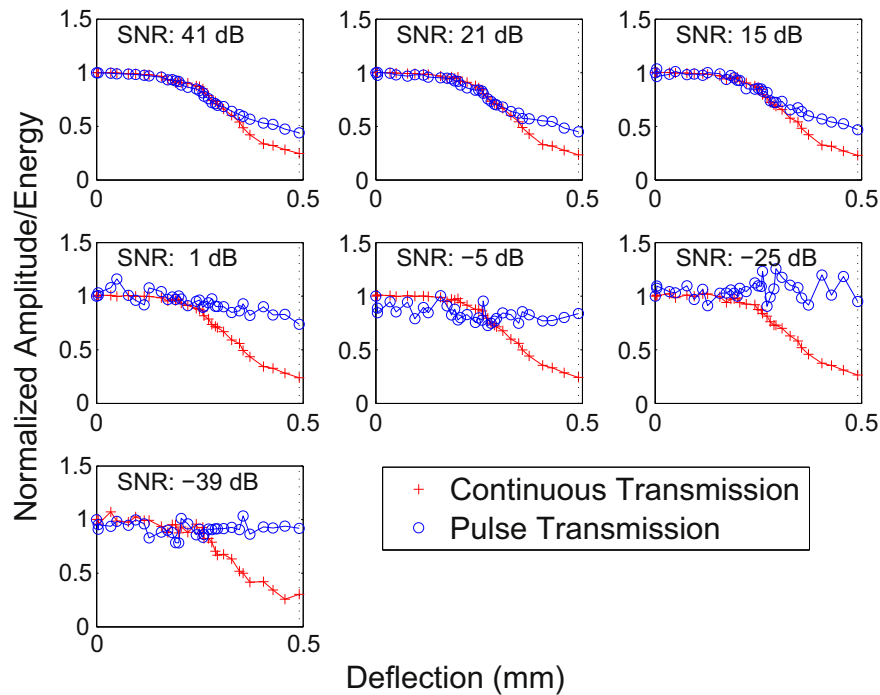


Fig. 5. Amplitude measurements from continuous measurements and energy measurements from pulse measurements as a function of deflection of the concrete slab. The amplitude and energy are normalized relative the baseline measurement. The horizontal axis of each subplot corresponds to the deflection of the concrete slab during the preceding load step. Each consecutive subplot shows measurements for decreasing signal-to-noise (SNR) ratio. The dotted, vertical line correspond to the deflection of the last load step before yielding.

is simply not measurable below the noise, even after averaging and filtering. The continuous signal data, however, measured by the lock-in amplifier, maintains its sensitivity to changes in the concrete even for extremely low signal levels; only for the lowest SNR is there some variance in the data at each load level. The results indicate that the continuous transmission display the same sensitivity as pulsed transmission, but is functional at lower signal levels.

4.2. Relative velocity/phase measurements

The relative velocity change of the pulses were computed using the stretching method in order to provide an indication of damage. The pulses measured after each load step were stretched with relative velocity change factors such as to maximize the correlation with the baseline signal. Fig. 6a shows the relative velocity change as a function of deflection of the concrete slab at the preceding load step. The figure shows data from the highest signal-to-noise ratio, ~41 dB. Fig. 6b shows the corresponding correlation after stretching. It can clearly be seen that the velocity decreases as the concrete is damaged. It can also be seen that the correlation decreases with increasing damage, since the shape of the pulse is increasingly warped. For very low values of correlation the corresponding value of relative velocity change is meaningless. This is the case after reinforcement bars have yielded, after ~0.5 mm deflection; the calculated velocity change is large, but the correlation is very low.

In order to compare the sensitivity of the time-stretch measurements for pulse transmission and the phase measurements for the continuous transmission, both data sets were normalized to the minimum value in the set of measurements before yielding of the reinforcement bars. These normalized relative values are shown in Fig. 7, as a function of previous deflection of the slab. Each sub-figure displays similar measurements with decreasing signal-to-noise ratio.

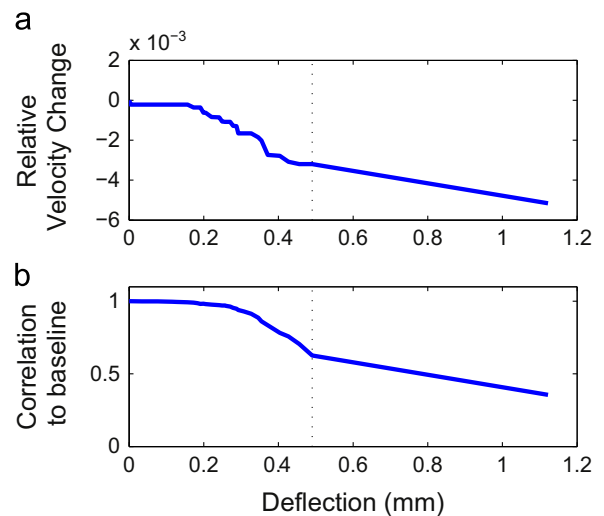


Fig. 6. (a) Relative velocity change as a function of deflection of the concrete slab, as calculated with the time-stretch method. Each value stretches the measured pulse in such a way as to maximize the correlation with the baseline. (b) Correlation with the baseline for each measured pulse after stretching with the optimal relative velocity change. The dotted black line corresponds to the deflection at breaking point for the slab.

As can be seen in Fig. 7, for the transmissions with high signal-to-noise ratio, the velocity and phase measurements display very similar sensitivity to damage, with a clear relation to the previously experienced deflection of the concrete slab. It should be noted that, after yielding of the reinforcement bars, the pulse measurements do not correlate to the baseline signal and the absolute values of these data are meaningless. These values are therefore not shown in the figure.

Similarly as for the attenuation measurements, in Fig. 5, it is clear from Fig. 7 that for very low SNR the pulse measurements cannot distinguish between the pristine and damaged concrete

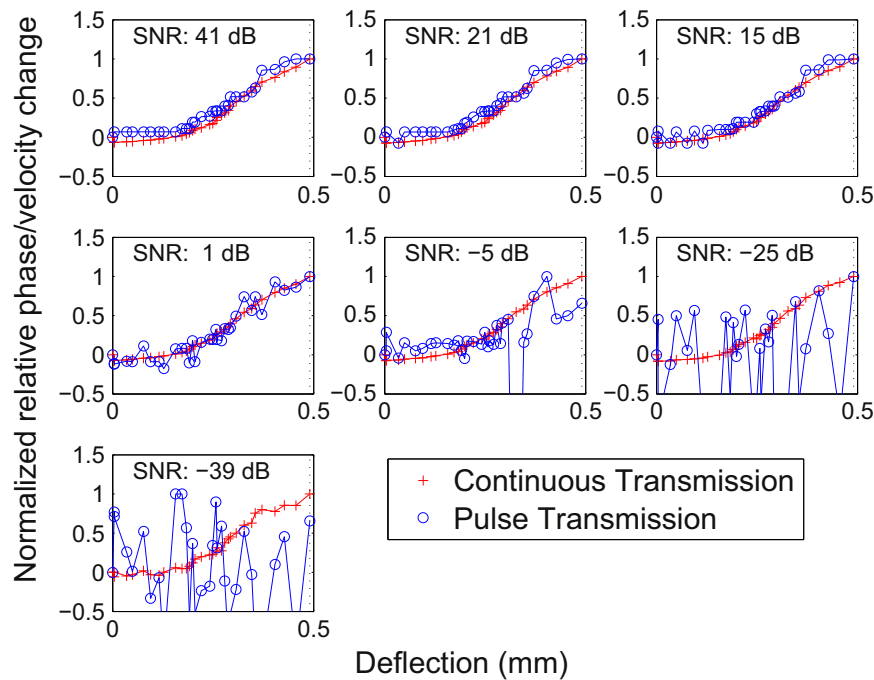


Fig. 7. Phase measurements from continuous measurements and relative velocity change measurements from pulse measurements as a function of deflection of the concrete slab. The phase and velocity change are normalized relative the minimum value of the set of measurements before the yielding of the reinforcement bars. The horizontal axis of each subplot corresponds to the deflection of the concrete slab during the preceding load step. Each consecutive subplot shows measurements for decreasing signal-to-noise (SNR) ratio. The dotted, vertical line correspond to the deflection of the last load step before yielding.

due to the signal being buried under the noise. The phase measurement maintains its sensitivity even at extremely low signal levels.

The results show that both amplitude and phase measurement of continuous waves give indications of damage equal to similar measurements with pulse transmission, with the added benefit of being able to detect much weaker signals. The pulse transmissions lose their sensitivity to damage when the measured signal is of the same order of magnitude as the noise, while the continuous measurements maintain their sensitivity even at a SNR of ~ -40 dB, and possibly lower. The presented pulse measurements are averaged with 20 samples. Theoretically, SNR increases with the square-root of the number of samples, provided that the noise is truly white and the channel is stable. Under such conditions, this means that the pulse measurements would need to be averaged 10,000 times in order to maintain sensitivity at -40 dB SNR.

The phase measurements give slightly earlier warning than the amplitude measurements, but both values are obtained simultaneously from the lock-in amplifier which means it is very little effort to design an SHM application which makes use of both parameters. The time-stretching method is computationally intensive as each measurement is correlated to many stretched baseline signals. In contrast, the phase measurements are read from the lock-in amplifier in almost real-time.

The results from the study indicate the usefulness of the measurement method for the specific concrete slab, with given dimensions and damage. However, an advantage with using multiple scattered waveforms is that increasing complexity in the geometry of the test object does not impede the measurements; more boundaries simply increase the diffusivity of the waveform. It should be noted that decreasing the transmission signal amplitude should be considered a rough approximation of increasing the distance between the transducers; in this experiment the geometry, and thus possible propagation paths, remain the same for the different simulated transducer distances. This is generally not the case for real life structures.

If continuous measurements are used, it is of great importance to establish that no parasitic electrical coupling exist between the transducers as this might hide the mechanical signal. This is less of an issue in pulse transmission, as transmission and reception is separated in time. In the presented study, this was done by observing that no signal was measured with the same experimental set-up, but with the transducers without contact with the concrete. Also, the fact that the measured signal clearly shows almost identical correlation to damage level in the concrete, as the pulsed measurements, greatly indicates that the coupling is mechanical.

The methodology demonstrated in this paper could make higher frequency signals practical in continuous monitoring of even large concrete structures. In this study signals with frequencies of ~ 50 kHz were used, which yields wavelengths of several centimeters. In order to detect smaller damage higher frequencies are typically used. For SHM purposes, however, this has not been practical due to the high attenuation in concrete.

The measurement procedure can easily be expanded to use signals with swept frequency. By sweeping across a suitable frequency range pulse measurements can be recreated with an inverse Fourier transformation. Sweeps which include lower frequency regions can utilize structural modes to possibly extend operational range further.

5. Conclusions

Amplitude and phase measurements of continuous, single-frequency ultrasonic signals as indicators of damage in a reinforced concrete slab have been evaluated. The measurements have been benchmarked to energy and velocity measurements of ultrasonic pulse measurements, with a central frequency the same as the continuous signal.

It has been shown that the continuous-signal measurements and pulse measurements display remarkably similar sensitivity to

damage, both with regard to attenuation and velocity changes, for the given excitation signals and specimen geometries.

Further studies are necessary to compare continuous transmission signals and pulsed coda wave analysis at other frequencies. It should be noted that other excitation signals for the coda wave analysis, such as chirps, can yield higher sensitivities, and that the sensitivity can be further increased by measuring nonlinear parameters, e.g. with low frequency wave modulation. The prospect of using similar nonlinearity measurements for continuous wave transmissions is of future interest.

The choice of time window in coda wave analysis is not trivial in applications with low SNR; particularly for nonlinearity measurements it has been shown that it is crucial to use very late parts of the signals [22]. However, the later parts of the coda are most obscured by noise and increased attenuation. There is thus a trade-off in sensitivity and robustness.

It has been demonstrated that continuous measurements, with a lock-in amplifier, can easily be performed at much lower signal levels than for pulse measurements, while maintaining the sensitivity to damage in the concrete. This suggests that it is possible to increase the transducer distance, or increase frequency, in SHM applications. This would be very beneficial in the monitoring of civil structures, as these can be very large and because the attenuation of mechanical waves is high in concrete. These measurements are also insensitive to variations in the noise environment of the monitored structure.

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