

## A Comparison Between Pulse and Continuous Guided Wave Pitch-Catch Testing of Concrete Beams

P. Fröjd, P. Ulriksen

Department of Engineering Geology, Lund University; Lund, Sweden  
Phone: +46 46 222 89 83; e-mail: patrik.frojd@tg.lth.se, peter.ulriksen@tg.lth.se

### Abstract

Measuring amplitude and phase of continuous ultrasonic waves with a lock-in amplifier is shown to give equally 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 levels. 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.

**Keywords:** Structural health monitoring (SHM), ultrasound, diffuse field, continuous wave, lock-in amplifier

### 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 field of non-destructive testing (NDT).

Structural health monitoring (SHM) can be regarded as a continuous version of more traditional NDT; a structure is permanently equipped with transducers which continuously, or regularly, perform measurements which give an indication as to its health status. Benefits of SHM systems, which differentiate it from traditional NDT, include the facts that no operators are necessary on site, inaccessible locations can be monitored and measurements can be taken very often, which in turn enables the detection of sudden events in the structure. An SHM system can monitor a structure for its entire lifecycle and each measurement is compared to a baseline [1].

Ultrasonic waves, with a variety of methods, have been successfully used in NDT of concrete structures [2], [3]. 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 [4]–[7]. 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 damage 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. 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 [8]–[12]. There exist different methods for analyzing coda waves, including the doublet method [5]–[7] and the stretching method [4], [13], [14] among which the latter of these has been shown to be more precise and more stable towards noise [15]. 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. [16], Liao et al. [17] and Song et al. [18] 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.

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 x 0.8 x 0.15 m 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. Figure 1 shows the layout of the reinforcement. The slab was cured for 31 days before the testing.

**Table 1. Composition of concrete.**

Components	Values (kg/m <sup>3</sup> )
Cement	400
Fine aggregate (0-8 mm)	890
Course aggregate (8-11 mm)	445
Course aggregate (11-16 mm)	445
Water	180
Superplasticizer (Sikament EVO 26)	0.83

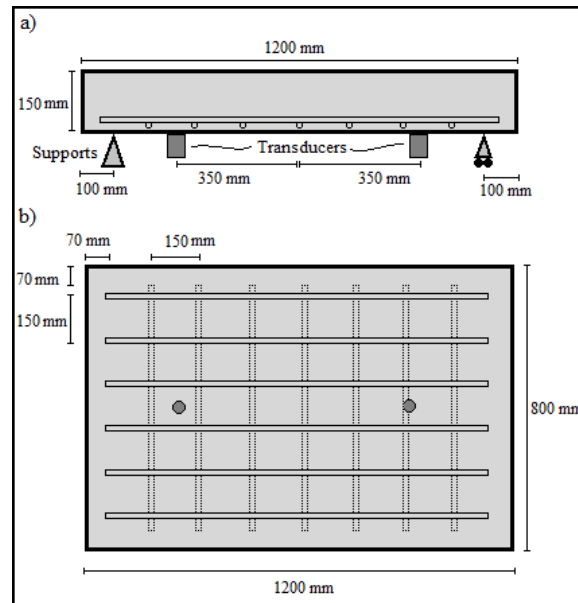


Figure 1. Concrete dimensions, reinforcement layout and transducer locations. Concrete slab seen from the side (a) and from above (b).

## 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. 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 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 Figure 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 two displacement transducers measured the deflection of the slab.

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 and 5 continuous transmission measurements were performed in order to enable averaging and statistics.

The choice of 47 kHz signals gives a surface wave wavelength of ~4 cm, which is slightly larger than the largest aggregates in the concrete. 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.

### 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 by calculating the energy dissipation and the stretching method [4], [13], [14]. 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  $k$ ,  $\Delta t$  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  $\alpha_i$  are different stretching factors. The  $\alpha$  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. 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.

## 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.

Figure 2 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.

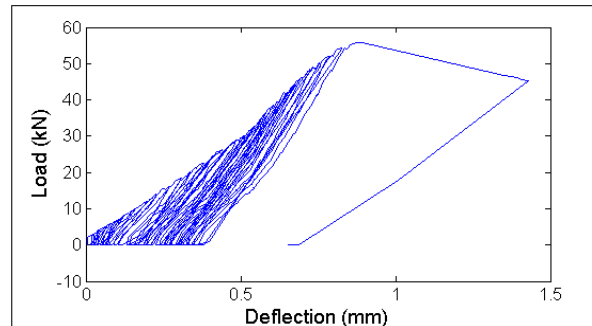


Figure 2. Response of the concrete to the loading procedure. The reinforcement bars yielded at ~57 kN load. Acoustical measurements were performed while the slab was not loaded.

### 4.1 Amplitude/Energy 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 figure 3 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 figure part 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 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.

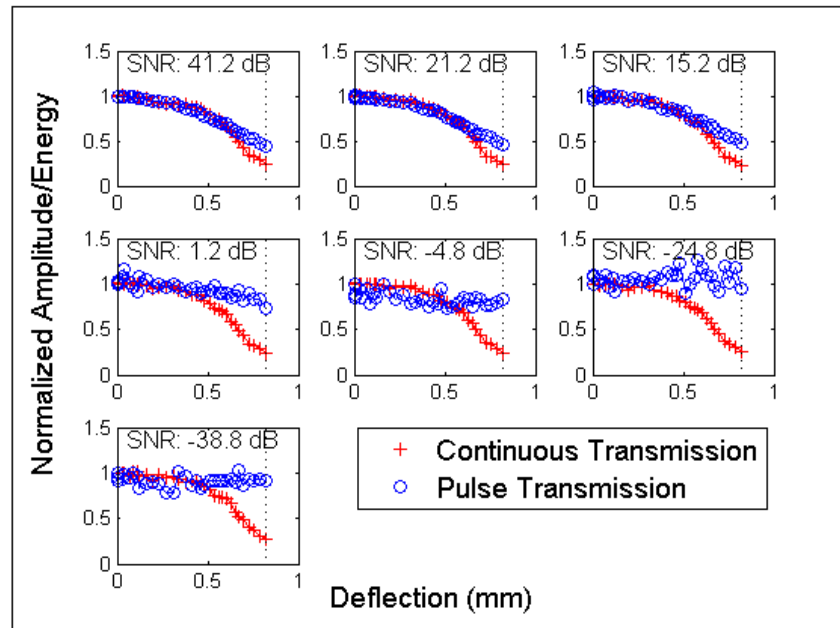


Figure 3. Amplitude measurements from continuous measurements and energy measurements from pulse measurements as a function of deflection of the concrete slab. The amplitude and energy are normalized relative the baseline measurement. The horizontal axis of each subplot corresponds to the deflection 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.

#### 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. 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 figure 4, as a function of previous deflection of the slab. Each subsequent figure part displays similar measurements with decreasing signal-to-noise ratio.

As can be seen in figure 4, 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 reinforcements 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 figure 3, it is clear from figure 4 that for very low SNR the pulse measurements cannot distinguish between the pristine and damaged concrete due to the signal being buried under the noise. The phase measurement maintains its sensitivity even at extremely low signal levels.

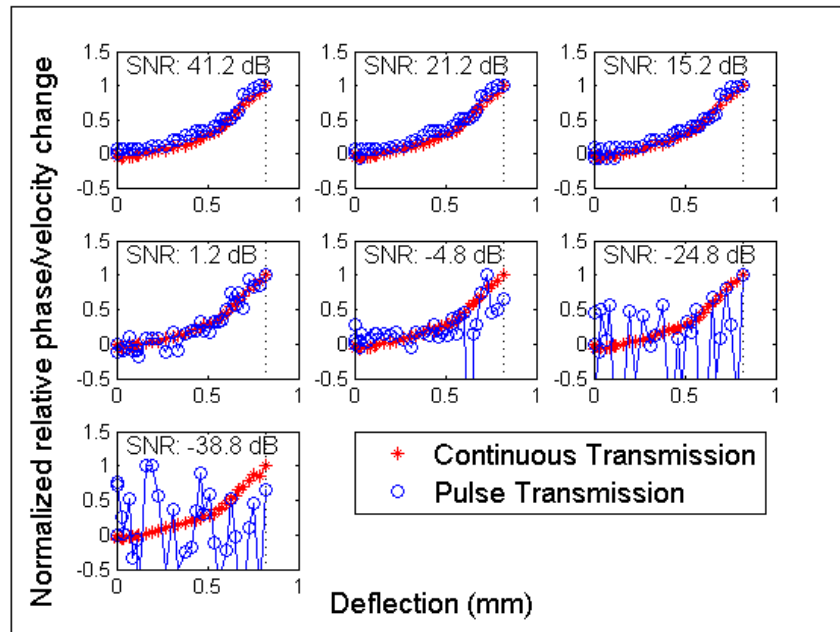


Figure 4. Phase measurements from continuous measurements and relative velocity change measurements from pulse measurements as a function of deflection of the concrete slab. The phase and velocity change are normalized relative the minimum value of the set of measurements before the yielding of the reinforcement 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.

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 the same order of magnitude as the noise, while the continuous measurements maintain their sensitivity even at a SNR of  $\sim -40$  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. This means that the pulse measurements would need to be averaged 10000 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 health monitoring of even large concrete structures. In this study was used signals with frequencies of ~50 kHz 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 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. Furthermore it has been demonstrated that continuous measurements, with a lock-in amplifier, can easily be performed at much lower signal levels than for transient 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 great in concrete.

## Acknowledgements

This work was supported by Swedish Research Council Formas [grant number 244-2012-1001].

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