NARROW-BAND DIFFUSE ULTRASONIC WAVEFIELD MEASUREMENTS IN A NETWORK OF RECIPROCAL TRANSDUCERS FOR MONITORING OF A LARGE CONCRETE FLOOR SLAB

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Abstract

Piezoelectric transducers were attached in a grid on the surface of an 8 x 2 x 0.08 m concrete floor slab. Through an automated, iterative scheme these were used to transmit and receive 50 kHz, continuous, sinusoidal signals, which were sampled by a multi-channel lock-in amplifier. The measured amplitude and phase were used to locate inflicted damage by detecting deviations from baseline measurements, acquired in a reference state. Superficial damage, in the range of centimeter, could easily be detected, even between the transducers placed the furthest apart, and could be located to a grid coordinate on the floor slab.

1 INTRODUCTION

In crucial concrete structures, such as dams and power plants, it is important to detect early signs of cracking and damage, as these can quickly lead to more severe damage, e.g. by exposing the reinforcement bars to the environment.

Many methods of non-destructive testing (NDT) exists, based on different physical phenomena. Ultrasonic waves are widely used for NDT in different applications, and has been successfully implemented for use in concrete structures.

However, traditional ultrasonic measurements can be problematic, in concrete, due to the severe scattering of the waves in the aggregates. This scattering redistributes energy from the coherent wave to a more diffuse propagation.

In coda wave interferometry (CWI), the trailing part of the transient signal is analyzed. These signals correspond to the diffuse field created by reflections from the boundaries and scattering from heterogeneities in the material. It is not possible to attribute features in the diffuse signal to any one specific bulk or guided wave mode, nor is it possible to determine the propagation path traveled by a wave corresponding to a particular part of the signal. However, it has been shown that CWI is very sensitive to changes in the material [1]–[4], due to the fact that the trailing parts of the measured signal correspond to waves that have traversed a relatively large volume, and have thus traversed the damaged region repeatedly. These waves have been more affected by damage in the material than the parts corresponding to the direct propagation path. Analysis of coda waves is an attractive prospect for structural health monitoring (SHM) applications, since not only the direct path between two transducers is probed, but a larger volume.

The literature describes numerous studies where CWI has been implemented in both NDT and SHM applications and investigated for its ability to detect early onsets of cracking in concrete [5]–[9]. There has been recent publications which report on methods to compensate for temperature effects on CWI measurements [10]–[12] and to measure nonlinear effects in the monitored material [13], [14], thus furthering the usefulness of diffuse field measurements in SHM applications.

However, one issue with coda wave analysis (and ultrasonic waves in general) in civil structures is the fact that mechanical waves experience substantial attenuation in concrete. This makes it difficult to cover large areas as the transducers have to be placed close together. For this reason, the prospect of detecting weaker signals, thereby increasing the transmission range, is appealing.

Continuous waves can be detected at weaker signal levels than transient pulses, and the use of such transmissions is one method of improving the detection capability, and thus increasing the useful range between transducers. If a single frequency is transmitted continuously, after a short period of time, a steady state will stabilize that consists of direct propagation, reflections from the boundaries, and scattered waves. The signal measured at any receiver location will be a superposition of all the different propagation paths between the 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 would otherwise rapidly attenuate below the noise floor. Furthermore, if a lock-in amplifier is used as a coherent detector, then continuous signals can be detected at low amplitudes, even well below the noise floor. This has the potential to increase the distance between transducers and thus enable the monitoring of larger structures given a fixed number of sensors. It also has the potential to measure higher signal frequencies, which are known to be more sensitive to damage but are quickly attenuated by the concrete at significant distances.

Yan et al. [15], Liao et al. [16], and Song et al. [17] used continuous waves 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. The damage to the concrete was correlated with a decrease in energy. Continuous wave transmissions was also proposed by Lobkis and Weaver [18] to monitor small changes in materials. In their work, the concrete acts as the propagation medium in an ultrasonic feedback system, and changes in the material were shown to affect the frequency of the resulting continuous tone.

We have previously shown that amplitude and phase measurements of continuous waves can be used to track increasing damage in a concrete slab subjected to bending loads, with similar sensitivity as CWI [19]. In this work it was also shown that the continuous wave measurement remained coherent and useful at very low signal-to-noise ratios, far below the functional limit of pulsed wave measurements, even after the filtering and averaging of the latter.

Locating damage in concrete, when using multiple scattered and reflected wave measurements, is not straight-forward due to the diffuse nature of the acquired signals. However, methods for locating damage has been proposed, based on modeling travel time variations and decorrelation of coda waves [20]–[22]. In these methods the multiply scattered propagating wave fields are approximated as diffusion or radiative transfer, and an inversion process is implemented to fit these analytical models to experimentally measured data. The use of the radiative transfer approximation in the LOCADIFF algorithm, proposed by Planès et al., has been shown to give good results even if the location of damage is located close to the transducers, by also considering the direct propagating wave [23].

These tomographic methods require full waveform measurements of the diffuse wave fields, which is why they are not applicable when transmitting continuous waves and measuring with a lock-in amplifier, since this yields only scalar values of amplitude and phase. Yan et al. [15] located damage to some degree, when using continuous waves, through dividing a shear wall into horizontal and vertical subdomains and assigning each domain the value of the damage index measured by one transducer pair per domain. A similar approach is used in this work; the structure under test is divided into a set of subdomains and each domain is evaluated by averaging amplitude and phase measurements from a large number of transducer pairs.

The purpose of this study is to investigate the possibility of detecting and locating any superficial damage on a large concrete floor slab using continuous wave measurements. Reciprocal piezoelectric transducers were surface mounted in a grid on the floor, and a monitoring system was implemented that enabled reciprocal measurements between all sensors in the network.

2 MATERIALS AND EQUIPMENT

The floor module was a composite of an 8000 x 2110 x 80 mm concrete slab on top of glued, laminated timber (glulam) beams. The glulam beams were attached to the concrete slab with screws that protruded diagonally from the beams and were cast into the concrete. Figure 1 shows a photograph of the floor slab. The water-cement ratio for the concrete was 0.442 and the largest aggregates in the mix was 11 mm. The concrete slab was reinforced with a steel mesh with a nominal diameter of 6 mm and 150 mm squares.

Figure 1: Photograph of the monitored concrete floor slab and the piezoelectric transducers used for measurements.

The ultrasonic waves were generated and measured using 30 piezoceramic discs (Ferroperm pz27), placed in a 3x10 grid on the surface of the concrete slab. The layout and numbering of the transducers are shown in Figure 2.

The excitation signal was generated by an Agilent 33500B waveform generator and amplified by an A.A. Lab Systems LTD A-303 Amplifier. Measurements were performed with a Signal Recovery 7210 multichannel DSP lock-in amplifier that can measure up to 32 channels simultaneously. The lock-in amplifier outputs the amplitude of the measured signal and its phase relative to the driver signal (provided by the waveform generator).

A custom-made multiplexer enabled switching the transmission and reception channels arbitrarily between the signal generator and the lock-in amplifier.

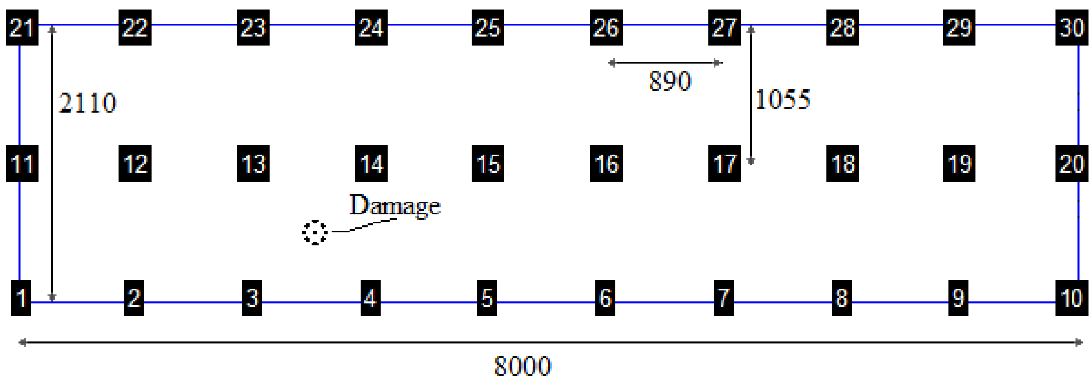

Figure 2: Layout and numbering of transducers. Dimensions are given in mm.

3 EXPERIMENTAL PROGRAM

For each measurement, one transmitting transducer was excited by a continuous 50 kHz sinusoidal wave. After the amplifier stage, the amplitude was 60 Vpp. The signal was left on for 100 ms before any measurements were made, providing sufficient time to reach a steady state. The lock-in amplifier measured the amplitude and phase at all 29 transducers that were not transmitting. The multiplexer then switched so that the next transducer in line operated as the transmitter and the rest as receivers. Thus, in each measurement cycle every transducer acted once as transmitter while all others acted as receivers. This resulted in 30x29 data pairs.

There was no external filtering or pre-amplification of the input signals to the lock-in amplifier.

Damage was gradually induced by use of a HILTI DX2 bolt gun with 6.8/11 M10 DX cartridges, power level “green” (“light”). The bolt gun was not loaded with any bolts, but the piston was used to inflict impact damage in a repeatable manner. The location of the shots on the floor slab is indicated in Figure 2.

The first shot was fired at the center of the area between transducers 3, 4, 13, and 14. Subsequent shots were fired in a 15 cm diameter circle around the location of the first shot. Figure 3 shows the order of the shots and the damage to the concrete. The visible damage to the concrete was superficial, with the deepest hole about 5 mm. The width of the holes varied from less than 1 cm to 4.5 cm. Some superficial cracking can be seen around the holes, e.g., around hole number 1.

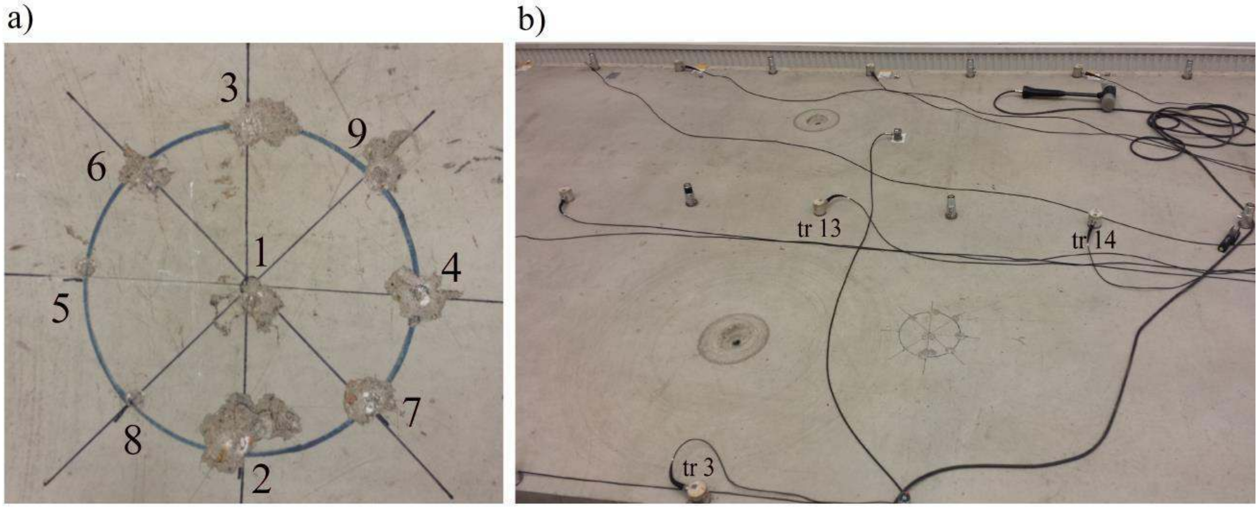

Figure 3: Photographs of the damage to the concrete from the bolt gun shots. a) Close-up of the damaged area. The numbers signify the order the shots were fired in. b) Damaged area in relation to surrounding transducers. Closest in-picture transducers are numbered. Also seen are other types of transducers, not referenced in this paper, and two of the threaded holes used for lifting the floor slab.

Ten measurement cycles were performed with the undamaged concrete floor slab. The data from the five first measurements are used as a baseline. After the measurements on the undamaged slab, shots were fired every five measurement cycles, resulting in 6 "damage levels". For the last damage level four shots were fired (corresponding to damage points 6-9 in Figure 3a).

4 DATA PROCESSING

The lock-in amplifier measured the amplitude and phase of the steady-state wave field at each receiver location, yielding two-dimensional measurements.

Each measurement was evaluated with the Mahalanobis distance [24], in amplitude-phase space, from the baseline data set. Equation 1 shows the Mahalanobis distance with transducer i as the transmitter and transducer j as the receiver.

$$D_{i,j} = \sqrt{\left(\boldsymbol{x}_{i,j}^{d} - \overline{\boldsymbol{X}_{i,j}^{b}}\right)^{T} \boldsymbol{S}^{-1} \left(\boldsymbol{x}_{i,j}^{d} - \overline{\boldsymbol{X}_{i,j}^{b}}\right)}$$

$\boldsymbol{x}_{i,j}^{d}$ is an amplitude and phase measurement from the potentially damaged structure, $\overline{\boldsymbol{X}_{i,j}^{b}}$ is the mean vector of the baseline data set, and $\boldsymbol{S}$ is the baseline covariance matrix. Superscript T indicates a transpose.

The Mahalanobis distance equals the distance from the mean of the baseline data set, expressed as the number of standard deviations of the baseline data in the specific direction in amplitude-phase space.

This damage indication system takes into account fluctuations in the baseline data set. If the baseline measurements have large variations in a certain direction in amplitude-phase space, then a larger absolute deviation from the mean of the baseline is needed in this direction to identify a measurement value as an outlier.

Since the continuous transmission will create a diffuse field through wave scatterings and boundary reflections, all pairs are affected by changes in the concrete, not just those pairs whose direct propagation path exactly crosses the area of damage. The benefit of this is that the waves reaching the receiver will have traversed the damaged area multiple times, and this yields high sensitivity. The drawback is that it impedes spatial localization.

However, there is some correlation to the transducer pair configuration relative to the damaged region. The attenuation in the concrete is such that waves that have traveled further will have less energy than those that traveled a more direct path. This means that the part of the wave corresponding to the direct propagation path, or close to this, contains the most energy. It is reasonable to assume that those transducer pairs with the damaged region between them are affected more by the damage than the other pairs. This reasoning agrees with the spatial distribution of the sensitivity kernels for the diffusion and radiative transfer models as shown by e.g. Planès et al. [23]. According to these models, the effect on the diffuse waves is greater if the change in the structure is located close to either transducer or in between them.

In order to investigate this, the floor slab was divided into a grid, with the same layout as the grid formed by the transducers. Each box in the grid was assigned a value corresponding to the mean of the Mahalanobis distance for all transducer pairs whose direct propagation path intersects the box.

5 RESULTS AND DISCUSSION

The lock-in amplifier enabled transmission between even the furthest transducers. The measured signal level between transducers 21 and 10 (distance of ~8.2 m) was on the order of 50 μV_{rms}. Signals of this level are far below the noise floor, but the impressive capabilities of the lock-in amplifier enabled their detection.

The previously described algorithm was used to investigate the possibility of locating the damage. The floor slab was divided into a grid, and the mean Mahalanobis distance (as calculated from measured amplitude and phase) of all transducer pairs that had a direct connecting line intersecting each individual grid box was calculated in a tomographic style. Figure 4 shows such data from one measurement at each of the different damage levels. The first subfigure, “level 0”, shows results from the measurements before any damage, but after acquisition of the baseline data set.

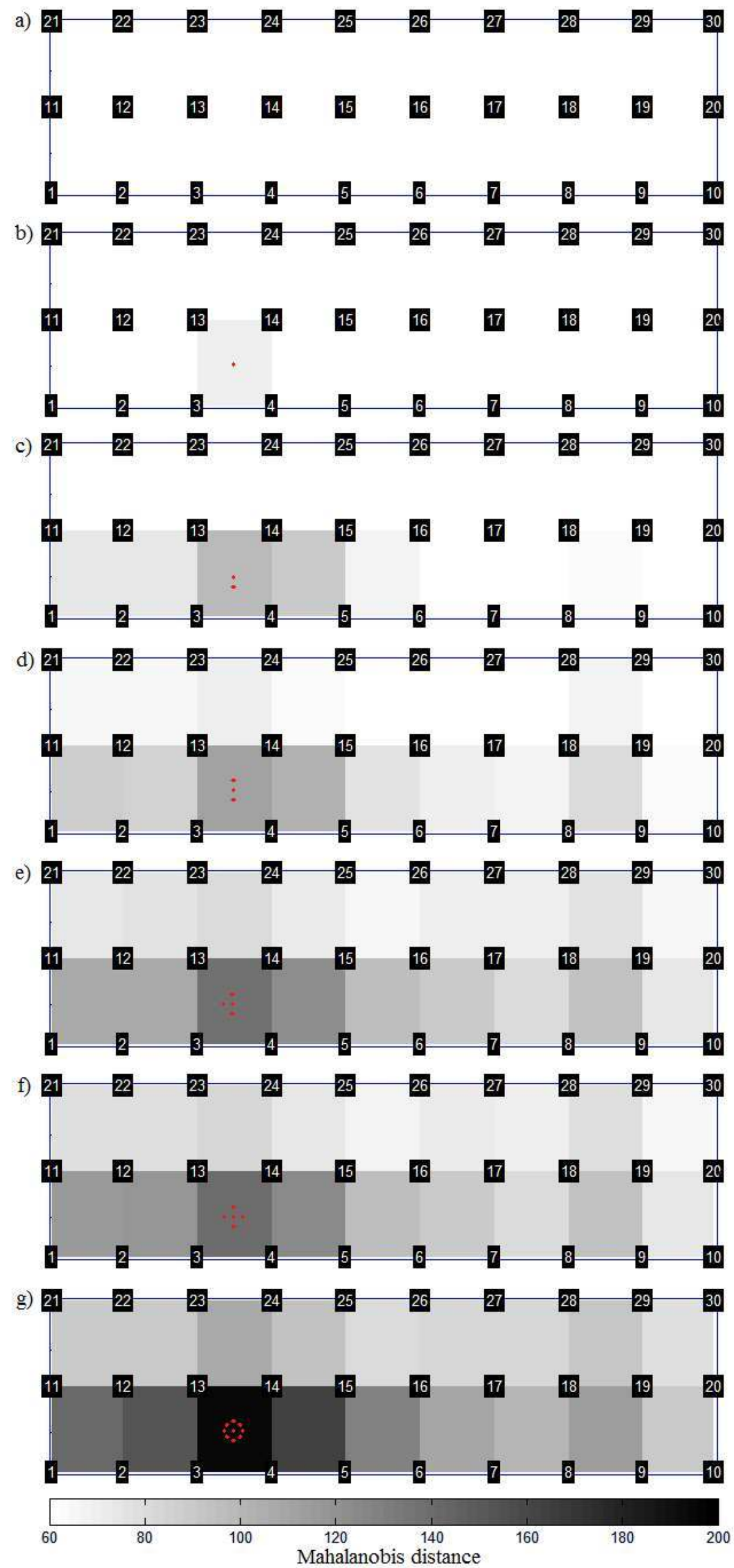

Figure 4: Mahalanobis distance from the baseline data for measurements at different damage levels. a)-g) damage levels 0-6. The red dots indicate locations of bolt gun shots.

The imaging method successfully identifies the grid coordinate of the damage as the box with the highest mean Mahalanobis distance from the baseline data. Additionally, it is evident that the deviation from the baseline increases as the damage level increases. This increase is seen over the entire floor slab, and there is a misleading particularly high indication in the grid box 8-9-18-19, but at all damage levels the correct grid box is assigned the highest value.

It should be noted that even the first damage level yields a mean Mahalanobis distance of 72 in the grid box corresponding to the damaged area. This is a substantial deviation, corresponding to 72 standard deviations from the mean of the baseline data set, and the possibility of detecting even slighter damage seems likely.

It is of interest to see if similar localization is possible with a sparser network of transducers. An example is shown in Figure 5a, where only transducers 4, 8, 11, 20, 22, 26 and 30 are used. It is evident from the figure that it is possible to localize the damage with sparser networks. Further removal of transducers resulted in a gradual loss of ability to locate the damage.

Figure 5b shows a lower resolution localization using only the data from the four transducers in the corners of the slab. This is encouraging for the scalability of the system; a system similar to that in the presented study but with several meters between the closest transducers would have great utility. Scaling the experiment is not straightforward, however, as the distance to the reflective boundaries affects the emerging diffuse wave field.

It should be stressed that the shading of the boxes in the grid is based on the means of all values from the transducer pairs with direct propagation paths crossing the box. Looking only at one or a very few pairs can yield false negative indications of damage in the vicinity of the pair or false positive indications at other locations. Further research is needed to fully understand this instability, but averaging over a number of transducer pairs mitigates the effects of such outliers.

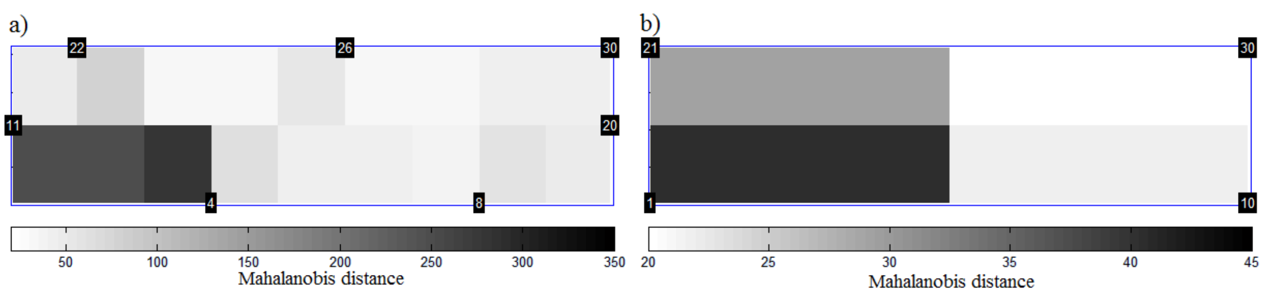

Figure 5: Mahalanobis distance from the baseline data for sparse networks of transducers at damage level 6. a) Transducers 4, 8, 11, 20, 22, 26 and 30 were used. b) Transducers 1, 10, 21, and 30 were used.

6 CONCLUSIONS

It has been shown that amplitude and phase measurements of single-frequency steady-state wave fields can successfully be used to detect small superficial damage in a concrete slab. The Mahalanobis distance from baseline measurements was used as indicator of damage. This distance increased as further damage was introduced to the floor slab.

Using a lock-in amplifier, useful signals were detectable even between transducer pairs placed 8.2 m apart. This was achieved with an excitation signal amplitude of 60 Vpp, which is relatively low compared to many other presented ultrasound-based SHM applications. An even greater range is expected if the excitation signal is increased further, although care must be taken when using continuous transmissions to avoid accidentally measuring the electrical coupling in the measurement system. The proposed measurement technique thus has the potential for monitoring even larger structures, with several meters between neighboring transducers.

Using a 50 kHz transmission frequency, it was possible to locate the damaged region to within an area slightly less than 1 m^2 through averaging of all transducer pair combinations.

Fluctuations are a source of error in the measurements. It is speculated that these fluctuations are caused by temperature variations leading to slight shifts in the transfer functions between each transducer pair, resulting in fluctuations in the efficiency of the chosen transmission frequency. A possible method to avoid this sensitivity is to step through a number of frequencies.

Further research is needed to be able to predict the effect of different changes in the material on the amplitude and phase of the transmitted signal between two transducers. However, by averaging the result over a number of transducer pairs and calculating the Mahalanobis distance from the baseline, it is possible to detect and locate damage and to differentiate between damage levels of varying severity.

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