

## Using embedded ultrasonic sensors for active and passive concrete monitoring

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### Abstract

Challenging new constructions and ageing infrastructure are increasing the demand for permanent monitoring of loads and condition. Various methods and sensors are used for this purpose. But the technologies available today have difficulties in detecting slowly progressing locally confined damages. Extensive investigations or instrumentations are required so far for this purpose. In this study we present new sensors and data processing methods for ultrasonic transmission, which can be used for non-destructive long term monitoring of concrete. They can be mounted during construction or thereafter. Larger volumes can be monitored by a limited number of sensors for changes of material properties. The principles of ultrasonic transmission and influencing factors are presented. This latter include load, damages as well as environmental parameters as temperature or moisture. Various methods for data processing, e. g. coda wave interferometry are introduced. They allow the detection of very small changes in the medium. The embedded sensors are shown including mounting and operation. Application examples so far include small scale laboratory freeze-thaw experiments, localizing loads in larger concrete models, monitoring load effects on real structures as well as detecting acoustic events. Some sensors are operating already for several years. The sensors can be used as transmitter or receivers or switched between both roles. While most of the previous experiments have been active (at least one sensor serving as transmitter), new studies show that the sensors are useful as well for passive measurements, e. g. in acoustic emission or time reversal experiments. Besides application in civil engineering our setups can also be used for model studies in geosciences.

**Keywords:** SHM, monitoring, ultrasound concrete, embedded sensors

### 1. Introduction

Currently, inspections of concrete constructions are mainly based on visual methods. Non-destructive methods are used more and more often. The use of bridge instrumentation increases rapidly. But so far monitoring is limited to local sensors (e. g. strain gauges), which are probing their close vicinity, or global methods as modal analysis, which looks to the structure as a whole. There is a gap in between. A method which would look at a certain critical volume of concrete with a very limited number of sensors would be of great value.

Ultrasonic transducers with frequencies from 25 kHz to 400 kHz have been used for concrete since decades. They are used in the lab on samples (and sometimes on site) in transmission mode to measure elastic properties and to assess degradation. New point contact transducers have revolutionized the use of echo techniques for thickness measurements and structural imaging. All transducers used in practice so far are for surface mounting. For monitoring this approach shows three strong disadvantages. First, the need for constant coupling, which is hard to realize on the surface in practice. Second, the high influence of surface and external effects (temperature and others) leads to unwanted effects on the measurements. Third, in practical field applications the transducers are prone for accidents or vandalism. Therefore a need for novel transducers, which can be permanently embedded in concrete has been identified.

## 2. The sensor

New ultrasonic transducers (“SO807”) have been designed by Acsys Ltd., Moscow, Russia in cooperation with BAM [1]. The main part is a hollow piezoceramic cylinder of 20 mm diameter and 35 mm length. The electric connections are on the inside. On both ends metallic pieces are clamped to the piezoceramic part. The outer diameter of 15 mm allows stacking of several transducers along a line using standard PVC tubes. Having all cables inside ensures good coupling of the piezo to the concrete and protects the electrical connections during installation. The total length of the transducer is 75 mm.



Figure 1. Sensor SO807

The amplitude spectrum of the sensor is shown in Figure 2. There is a prominent frequency peak at 62 kHz and a significant second one at 65 kHz. Smaller peaks appear around 50 and 85 kHz. There is no significant energy with frequencies lower than 40 or higher than 90 kHz. A frequency of 62 kHz relates to a wavelength in concrete (compressional wave speed of about 4000 m/s) of ca. 65 mm. This is at least double the size of most aggregates (max aggregate size 32 mm in many types of concrete).

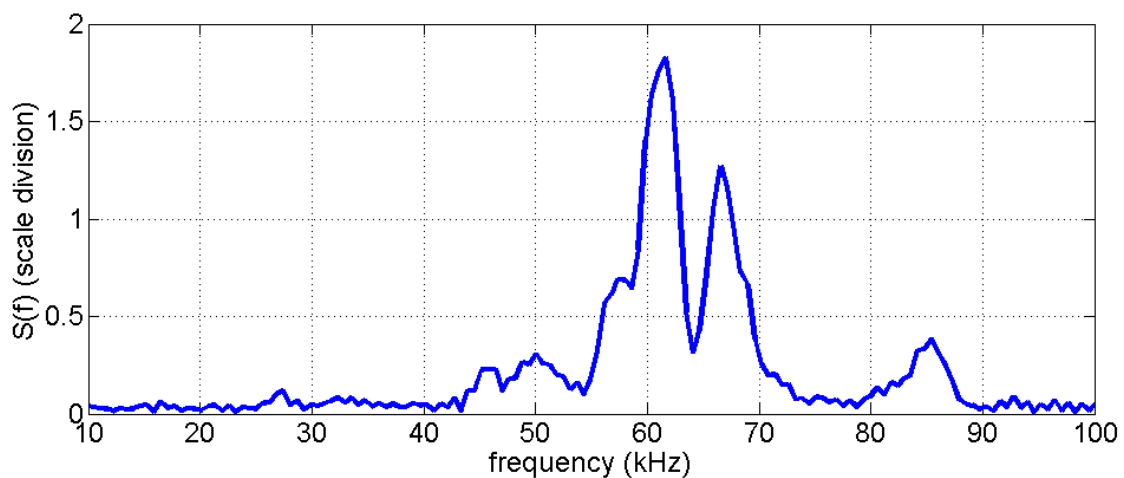


Figure 2. Amplitude spectrum of SO807

### 3. Applications

From literature it is known that the velocity of ultrasound changes with stress applied to the medium through which the ultrasound travels. Therefore ultrasonic measurement systems can be used as stress (change) indicators. This could be demonstrated by a laboratory experiment [2]. A concrete block had been equipped of 18 ultrasonic transducers. In the upper half of the concrete block a hole was drilled to insert a thread bolt. Nuts, 10·10 cm<sup>2</sup> load distributing plates and a piezo load cell provided a way to introduce localized compressional stress in a controlled, repeatable way (Figure3). Load steps of 5 or 10 kN were applied in various cycles up to a maximum load between 20 and 100 kN, more than one order of magnitude below the compressive strength of the concrete.



Figure 3. Concrete specimen GK32 with embedded transducers and load application system. From [2].

There are various ways to process the information provided from the ultrasonic measurements. While simple time of flight measurements don't provide accurate values for small velocity changes, other techniques as correlation analysis (fast, qualitative, easy to implement in online systems) or coda wave interferometry (more computationally expensive, quantitative, imaging available) provide information even for subtle effects [2], Figure 4 shows the change of correlation with load change.

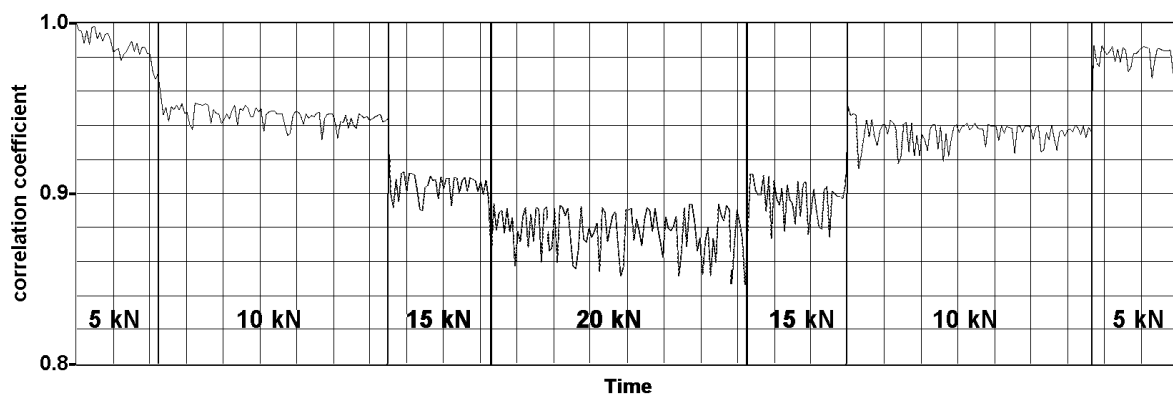


Figure 4. Correlation coefficient of 5 ms time series (reference: measurement at zero load) of ultrasonic signals measured by embedded transducers in a concrete block under small local compressional load. From [2]

Other applications include but are not limited to:

- Acoustic emission
- Detecting changes in crack density
- Early warning systems for damages (ASR, freeze-thaw ...)
- Time reversal experiments

We already have equipped more than a dozen of concrete objects and two operational bridges with our embedded sensors.

#### **4. Conclusions and Outlook**

The ultrasonic transducers developed for embedment in concrete have shown to be valuable tools for various tasks in structural monitoring. They met our expectations in frequency (around 60 kHz), directivity (almost circular around the main axis) and range (at least three meters). The transducers proved to be very robust. We have developed deployment systems for existing and newly built structures. Early versions are now embedded and used in lab samples and real structures for a few years and are still fully operational.

The embedment in concrete has various advantages: The coupling to the concrete is constant, transducers at lab samples have not to be removed before putting them into climate chambers, chemical baths or similar and installations are more vandal proof and less accident prone on existing structures.

#### **References**

1. Niederleithinger, E., J. Wolf, F. Mielentz, H. Wiggenhauser, S. Pirskawetz, 2015, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring. *Sensors* 15 (5): 9756–72. DOI: 10.3390/s150509756.
2. Niederleithinger, E., C. Sens-Schönfelder, S. Grothe, H. Wiggenhauser, 2014, Coda Wave Interferometry Used to Localize Compressional Load Effects on a Concrete Specimen. In: *Proceedings of EWSHM 2014, Nantes, 2014.*