Implementation of Ultrasonic Coda Wave Interferometry on a Real Bridge

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ABSTRACT

Urbanization becomes increasingly important in our modern life. This is undoubtedly a huge opportunity and challenge for construction industry. More and more bridges are constructed to improve the infrastructure and develop the economy. For more than a century, reinforced concrete bridges are the most common bridges due to its durability, relatively low maintenance cost and rapid construction. In general, concrete bridges are designed to ensure a service life of at least 100 years. However, mechanical and environmental factors or excessive use accelerate the deterioration of the bridges. Some bridges even failed in their early-life. Thus, we are faced with the necessity to monitor health condition of bridges at every moment during their life which is also the aim of Structure Health Monitoring (SHM). Most deterioration and failure mechanisms are connected to the development of micro- or macro-cracks. Ultrasonic Coda Wave Interferometry (CWI) method using diffuse wave is one of the most promising method to detect subtle changes and cracking in heterogeneous materials such as concrete. Moreover, the data acquisition system has a high portability and the size of data recorded is small. If needed, even real-time assessment can be performed with an optimized algorithm. Embedded ultrasonic sensors can be installed inside the structure to avoid changes in coupling or excess influence of environmental influence factors. The measurements will focus more on the internal of the structure. Research shows that CWI has high sensitivity in detecting temperature change, stress variation and cracks in laboratory size concrete specimens. A young reinforced concrete road bridge in Gliwice, Poland has been monitored in a first step. Results have shown that the bridge is in good condition. However, the method has so far not been implemented on existing middle-aged bridge. In this paper, the monitoring of a 46 years old reinforced concrete road bridge close to Cologne, Germany will be discussed. Multiple sensors (thermocouples, strain gages and embedded ultrasonic sensors) were installed in the bridge. The bridge will be monitored for at least one month and subjected to a load test. As a result, the influence of temperature should be detected and quantified and a diagnosis of the bridge condition (especially changes in cracks) should be established.

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INTRODUCTION

Sonic and vibration measurement methods are widely used for structural health monitoring (SHM) application due to the easy implementation and non-destructive features. Since the diffraction and attenuation of elastic waves in concrete is pronounced, a relatively low frequency is usually adopted to generate elastic waves in concrete [1]. This method is normally done in a frequency range between 500 Hz and 10 kHz [2]. The wavelength is larger than the size of many aggregates and typical defects, thus the sensitivity to microscopic features are limited. When the measurements are performed in a frequency that exceeds 50 kHz, the waves interact with small heterogeneities. [3]. Ultrasonic pulse velocity (UPV) test is the most common ultrasonic method to assess the quality of concrete by measuring the time of flight (TOF) of ultrasonic waves. The products based on this method are commercially available. However, when the change or damage in the structure is relatively small which doesn't have detectable influence on the first arrivals, UPV method is not applicable anymore. To reach a higher sensitivity and do early-stage damage monitoring, CWI method from seismology were developed. CWI method has shown a great sensitivity to stress change and cracks opening in small laboratory size concrete specimen [4] and in large reinforced concrete beam under outdoor environment [5]. This method was also successfully implemented on a real bridge in Gliwice, Poland. Weak temperature induced velocity change has been detected [6]. Nevertheless, the experience and usability of CWI method on real civil engineering structures are still insufficient. In this paper, installation of a novel type of embedded ultrasonic transducer using a new developed method are explained in detail.

CODA WAVE INTERFEROMETRY

In heterogeneous medium, waves propagate along the multiple scattering trajectories. They are much more complicated than the direct wave or simple reflected ones. Coda wave is a sum of these waves which have repeatedly sampled the medium. Minor changes in the medium are amplified by these repeated sampling [7]. Therefore, it has a higher sensitivity to detect weak perturbations in the medium. The principle of CWI method is to compare two signals recorded in different states. Coda waves are highly repeatable, when there is no change in the medium over time, the waveform doesn't change.

The basis of CWI method are velocity change (dV/V) and correlation coefficient (CC) which measures the similarity between different signals. When the change in the medium is relatively small, the first arrivals don't change (i.e., figure 1 [0.16 ms, 0.35 ms]) while the coda wave (i.e., figure 1 [1.5 ms, 1.7 ms]) shows a change in waveform and small time-domain perturbation. In this case, the velocity change is considered as a dilation or compression in time by a factor (α) [8]. A chosen reference signal is stretched by different factors α in a range [-α_{max}, α_{max}] with a resolution of 10^{-5} or even 10^{-6}. CC between the signal recorded in a new state $u_p(t)$ and all the stretched reference signals $u_u(t(1+\alpha))$ will be then calculated. The α which maximize the $CC(\alpha)$ is chosen as the velocity change.

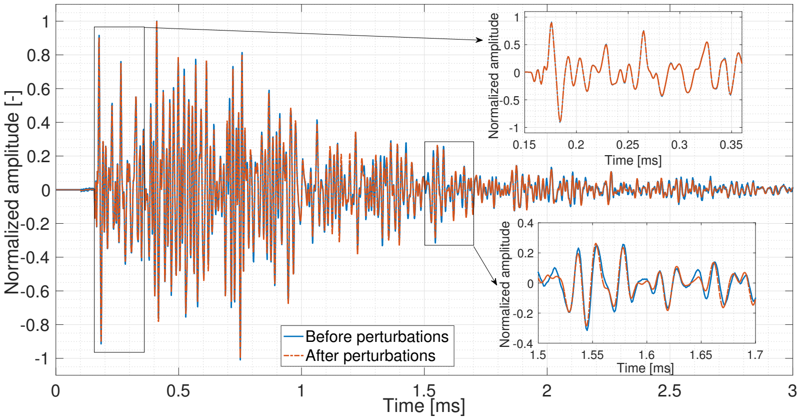


Figure 1. Signals recorded before and after small perturbations in the medium.

$$CC(\alpha) = \frac{\int_{t-T}^{t+T} u_u(t'(1+\alpha))u_p(t')dt'}{\sqrt{\int_{t-T}^{t+T} u_u^2(t'(1+\alpha))dt' \int_{t-T}^{t+T} u_p^2(t')dt'}} \tag{1}$$

Stress and temperature induced velocity variation are normally relatively small. When the velocity varies more than 1%, crack opening can be indicated. In this case, velocity variation can be directly measured by conventional TOF method [9].

EXPERIMENTAL SETUP

Bridge at Cologne

A bridge located at Cologne in Germany, constructed in 1972 was provided by BASt (German Federal Highway Research Institute). Eight ultrasonic sensors were planned to install inside the bridge in 2019. The tested bridge section was about 23 meters long and 15 meters wide. Detailed bridge dimensions and sensor locations are shown in figure 2.

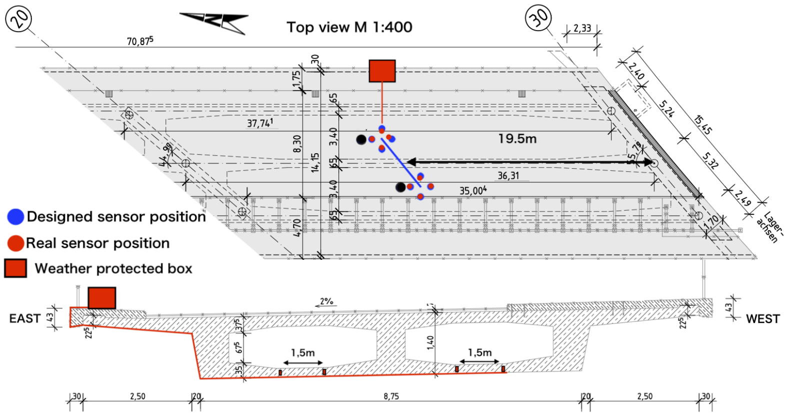


Figure 2. Drawing of the top view and cross-section of the bridge.

(a) [8]

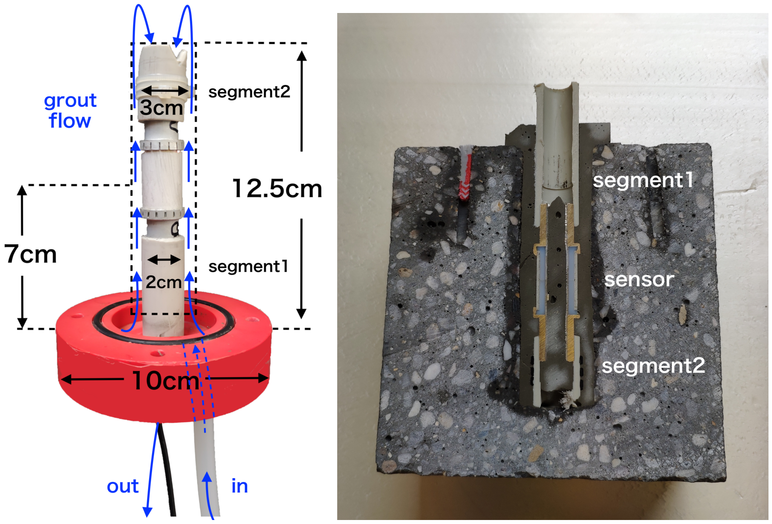
(b)

Figure 3. (a) Mounting SO807 to reinforcement with 3D-printed adapters on new bridges; (b) Mounting SO807 with L- shaped rebar on Gliwice bridge.

Installation of sensors

The traditional way to do ultrasonic monitoring is to glue the ultrasonic transducers on the surface of the structures. To focus on the interior of the structure and reduce the influence of near-surface changes, a new type of embedded ultrasonic sensor SO807 was invented [10]. The sensor could be mounted easily onto the reinforcement by attaching some 3D-printed adapters or a L-shaped rebar during the construction of the concrete structures before casting (figure 3).

The challenge now is to install the sensors inside existing structures. A special method was developed. A 'sensor module' was designed as shown in figure 4 (a). This module contains a ring with a rubber band, one normal PVC tube segment on the bottom which controls the depth of sensor, one SO807 transducer and one special PVC tube segment on the top. Three self locking cables were wrapped on this special segment and



(a)

(b)

Figure 4. (a) Sensor module and grout flow; (b) Longitudinal section of the tested specimen

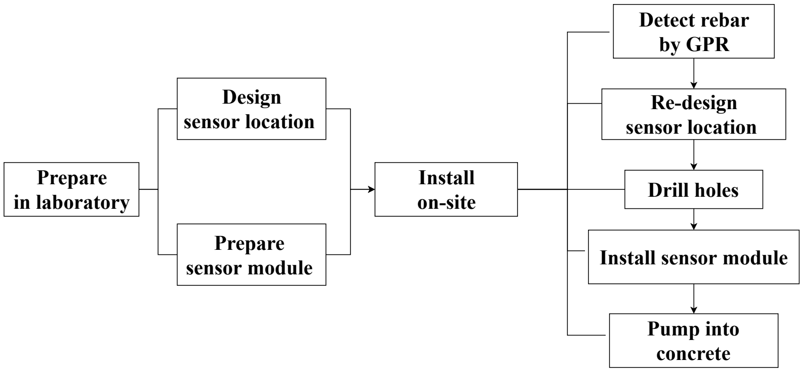


Figure 5. Diagram of work process.

some notch were cut at its end to ensure the smooth circulation of the grout.

This method was tested on a small concrete specimen in laboratory. First, a hole with a slightly bigger diameter than the transducer and slightly deeper depth than the installation depth was drilled. Then the sensor module was placed into the hole and fixed by two screws. A fast hardening and slightly expanding type of grout was then pumped in through the inlet. The rubber band ensured the sealing of this module. The grout filled the spaces between the sensor module and the concrete gradually. When the grout came out through the inner hollow space of the sensor and PVC tube, it is a signal that all the gaps were fully filled, By then, the inlet was blocked. 24 hours later, the tested specimen was cut into halves, the longitudinal section are shown in figure 4 (b), this installation method ensures sufficient coupling of the sensors to the concrete.

Implementation on real bridge

The entire installation process followed figure 5. The first-phase preparation included designing sensor positions and assembling sensor modules in laboratory.

When this method was implemented on-site, the situation was always more complicated in realistic. The position of the drilled hole should avoid hitting the reinforcement inside the bridge. Moreover, there shouldn't be any void (figure 6 (b)).) in the direct path

(a)

(b)

Figure 6. (a) Detecting rebar by GPR (Ground-penetrating radar); (b) Real position of the sensors

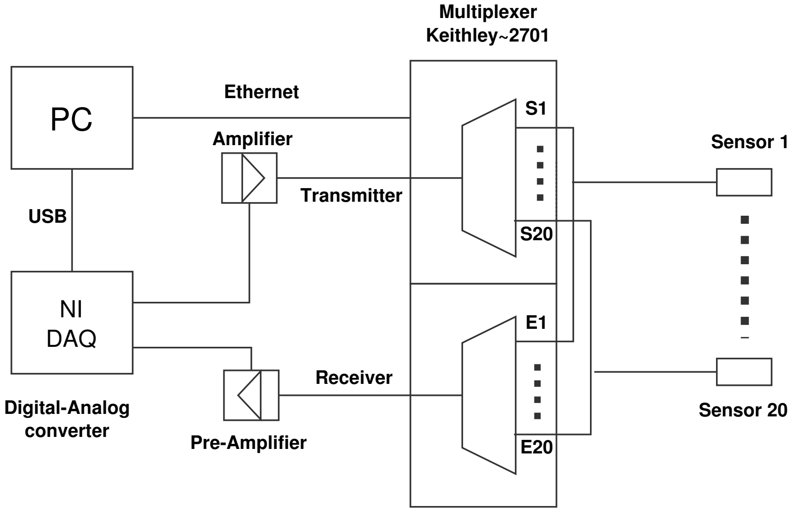


Figure 7. Sketch of the data acquisition system.

between two sensors.

The positions of sensors were designed as follows: the distance between two adjacent sensors is 1.06 meter and that between two diagonal sensors is 1.5 meters (figure 2 blue circle). However in real case, the position of the sensors were redesigned due to the structure itself (figure 2 red circle and figure 6 (b)). All the cables coming out from the sensors were placed in the PVC tube for better protection.

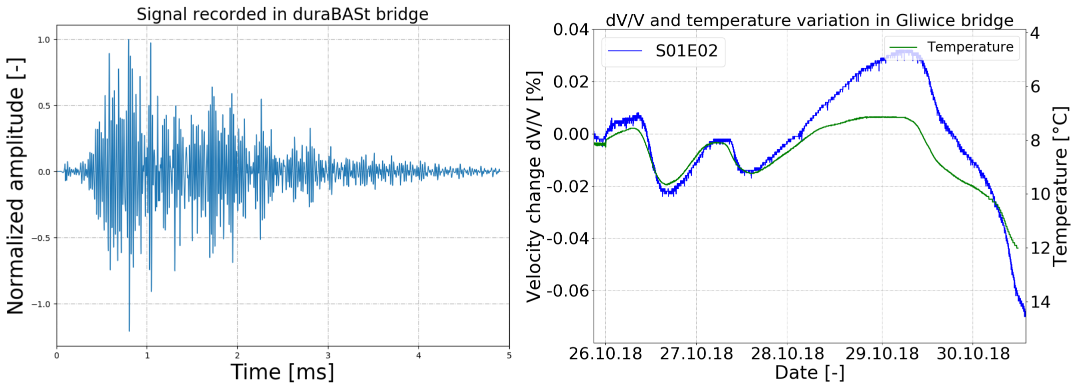
Data acquisition system

The data acquisition system (figure 7) contains an amplifier to amplify the input signal of the transmitter, a pre-amplifier with analog filter to improve the recorded signal from the receiver, a digital-analog data acquisition module and a multiplexer to switch between different combinations of sensors for the measurement.

This system allows continuous monitoring with a sampling frequency of 1 MHz. Measurement interval, number of samples and sequence of combination of sensors could be configured by the measurement program on PC. All the devices were locked in a weather protected box (figure 2).

PRELIMINARY DATA

A signal was recorded 24 hours after the installation by combination of transducers 01 and 04 (figure 8 (a)). The distance between these two sensors are 1.1 meters. The result shows that the coupling of the sensors and the concrete bridge are satisfactory. As the duraBASt bridge is still under monitoring, a monitoring result from Gliwice bridge is shown in figure 8 (b). The velocity change measured by combination of sensors 01 and 02 corresponds well to the temperature variation during the 5 days monitoring. The distance between these sensors are 1.15 meters. The variation of the velocity is less than 0.1% which is not detectable by classic ultrasonic methods.



(a) (b)

Figure 8. (a) Signal from combination of sensors transmitter 01 and receiver 04 in duraBASt bridge; (b) Velocity change and temperature variation in Gliwice bridge

CONCLUDING REMARKS

The study shows the feasibility of installation of SO807 ultrasonic sensors in existing structure after the construction. The preparation of sensor module was uncomplicated and the installation process was fast. However, the manipulation on-site was more complicated than ideal condition. The reinforcement and existing holes increased the difficulty of installation. The bridge is still under monitoring at the moment. After the monitoring, a general health condition of the bridge will be established. For further planning, static load test will be done on this bridge to study the sensitivity of CWI method to stress change on real bridge and reliability and practicality of this new installation method.

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