Monitoring a concrete bridge girder with the coda wave interferometry method

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ABSTRACT: Concrete bridges play an important role in the construction of urban infrastructure. Environmental factors and excessive use accelerate the aging of bridges. The collapse of bridges can cause casualties and serious economic losses. Hence, more and more people realize the necessity of structural health monitoring. Coda Wave Interferometry (CWI) technique for ultrasonic data is considered as one of the most promising methods to monitor concrete structures due to its high sensitivity to weak perturbations in a heterogeneous medium. Large structures can be monitored using a limited number of sensors. Previous research has shown that CWI successfully detects temperature and stress changes in laboratory size concrete specimens. However, up to now, because of the complexity of the outdoor environment, CWI technique hasn't been implemented on any real bridges. In this paper, a 36 meters long bridge girder in Gliwice, Poland, instrumented with different types of sensors (embedded ultrasonic sensor, strain gauges and thermocouple) inside the middle part will be studied. The bridge was monitored for 5 days. For preliminary evaluation, the influence of traffic and temperature could be detected and future improvement for long term monitoring could be discussed and planned.

1 INTRODUCTION

In tradition, nondestructive sonic methods are widely used for structural health monitoring (SHM) applications. This method is normally done in frequency range between 500 Hz and 10 kHz (McCann et al (2001)). When the working frequency range exceeds 50 kHz, waves enter multiple scattering regime and interact with heterogeneities in concrete (Planès et al (2013)). Ultrasonic pulse velocity (UPV) test is one of the most common ultrasonic methods to evaluate the quality of concrete in civil engineering. Ultrasonic transducers are contacted or glued on the surface of the structure to do the measurement. Pulse velocity are estimated by time of flight. The porosity and cracking influence the UPV (Saint-Pierre et al. (2016)). Higher velocities indicate better quality of concrete. However, when the change or damage in the structure is relatively weak, the traditional methods are not applicable anymore. To reach a higher sensitivity, a new method Coda wave interferometry (CWI) using diffuse waves has been developed. To focus on the interior of the structure and reduce the influence from near surface, a novel type of embedded ultrasonic transducers “SO807” was used for the measurement. Several studies have shown the easy installation of SO807 (Bassil et al. (2019)) and high sensitivity of CWI method to stress change and cracks opening (Wang et al (2018)). These experiments have been carried out in a short period of time, the influence of the temperature was negligible. In this study, the bridge was monitored for 5 days, so temperature played a more important role.

2 CODA WAVE INTERFEROMETRY

As multiple sacttered waves travel much longer time and along more complicated path than direct waves or simple reflected ones, they have higher sensitivity to detect weak perturbations in the medium. Coda waves are highly repeatable, if there is no change in the medium, the waveform doesn't change. As shown in Figure 1, two signals were recorded before and after weak perturbations in the media, the time of flight of the two signals are almost identical, small time-domain perturbations appeared only in the later arrivals. The principle of CWI is to detect changes by analyzing the coda waves (later arrivals) recorded in different states. The basis of CWI method is velocity change and correlation coefficient.

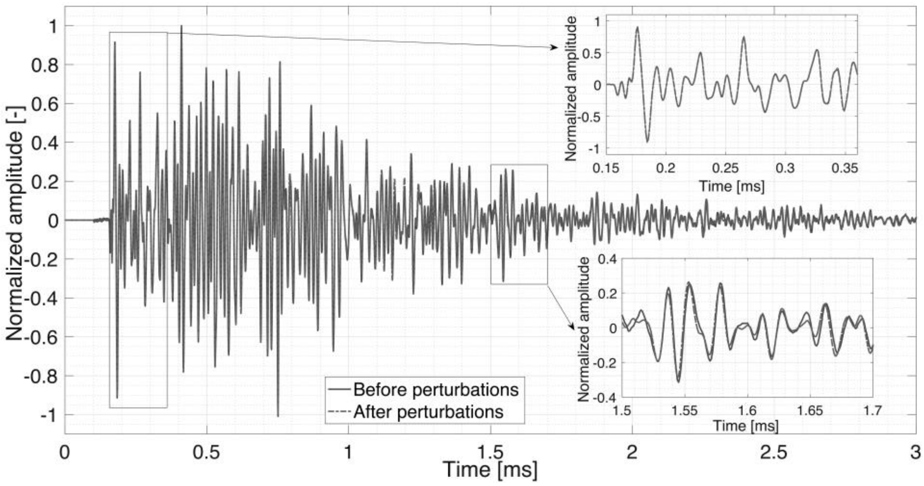


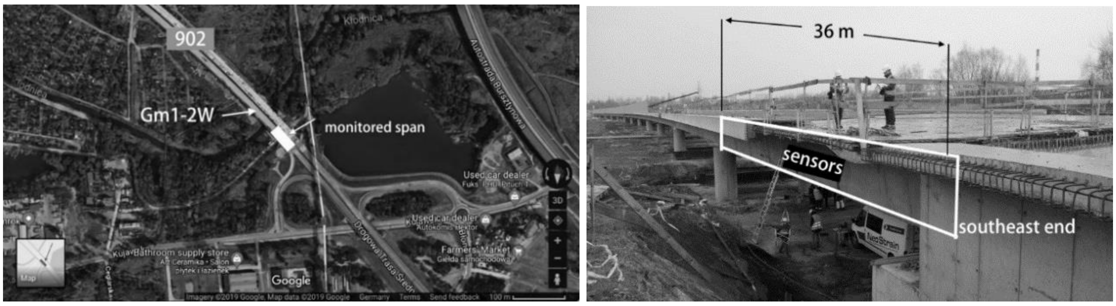
Figure 1. Signals recorded before and after small perturbations in the medium (Wang et al (2018)).

The most promising method for CWI algorithms is the stretching method. The velocity change is considered as a dilation or compression in time by a factor α (Niederleithinger et al. (2018)). First, a signal $u_u(t)$ recorded in the initial state is chosen as the reference signal. The signal will be stretched by the dilation factors α in range [αmin, αmax]. Normally, the absolute value of α is smaller than 1%. Then, the cross correlation between the signal $u_p(t)$ and all the stretched reference signals $u_u(t(1+\alpha))$ will be calculated. The dilation factor α which maximizes the cross correlation is considered as the velocity change. And the cross correlation corresponds to this is chosen as the correlation coefficient.

3 EXPERIMENTAL SETUP

3.1 Gliwice bridge

The bridge Gm1-2W is an extension of highway 902 connecting Katowice and Gliwice in Poland (Figure 2). It is a posttensioned concrete bridge supported by two girders. The 36 meters long span at the southeast end of bridge was selected as research object. The middle part of the girder which withstands the biggest stress change was chosen to be monitored. Ultrasonic sensors, thermocouples and vibration wire strain gauges were installed in this area during its construction in 2015 (Figure 1 (b)).

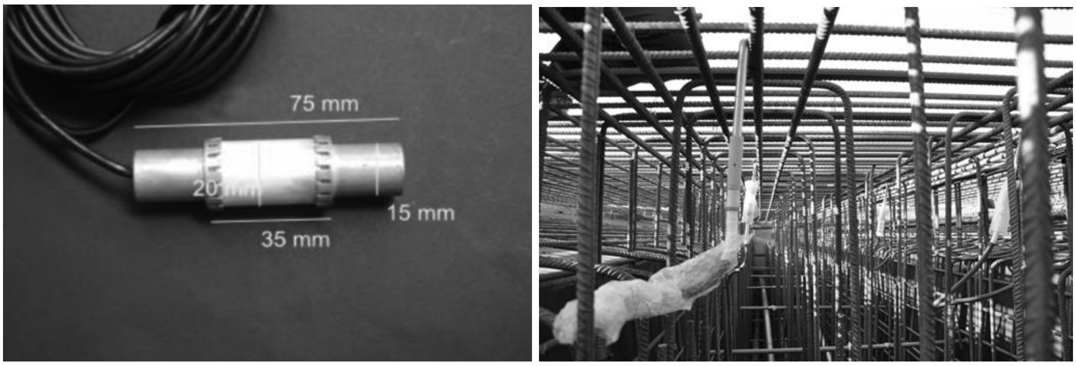


(a) (b)

Figure 2. (a) Location of Gm1-2W (Google map). (b) Monitored bridge span at southeast end

3.2 Installation of transducers

"SO807" is a new type of embedded ultrasonic sensor. The main part of SO807 is a hollow piezo-ceramic cylinder (Figure 3 (a)). This sensor can function as both transmitter and receiver. PVC tubes can be easily connected to the end metallic piece which simplifies the installation. As the sensors were installed inside the structure, they were protected well from the external environmental factors. After 4 years, these sensors were still functioning well.



(a) (b)

Figure 3. (a) Ultrasonic transducer SO807 (Niederleithinger et al. 2015). (b) Mounting sensor with L-shaped rebar.

SO807 sensors were mounted inside the girder during its construction before casting. A L-shaped piece of rebar was used to fix the position of the sensor. One end of the rebar was welded to the reinforcement and the other end was connected to the sensor by a piece of PVC tube (Figure 3 (b)). Eight ultrasonic sensors were installed around the center of the span (Figure 2). The arrangement of the sensors allows long and short range measurements.

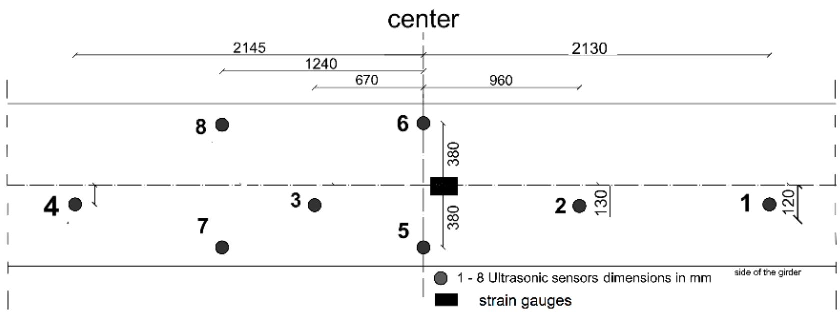


Figure 4. Arrangement of SO807 sensors and strain gauges in the girder

3.3 Data acquisition system

The data acquisition system contains (Figure 5):

- A laptop in which a measuring program is installed to configure and control the measurement
- An amplifier and a pre-amplifier to amplify and filter signals
- A multi-channel data acquisition module
- A multiplexer to switch different transducers combinations

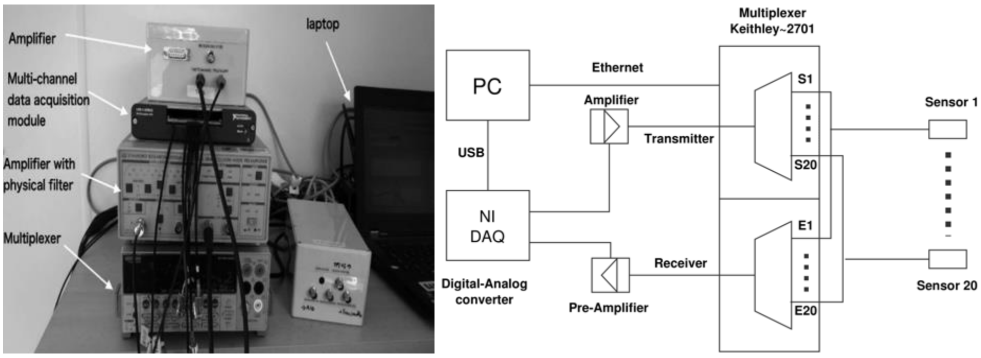


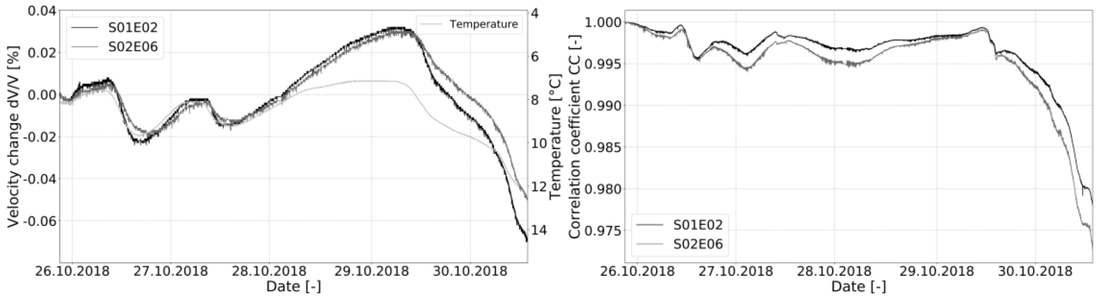
Figure 5. Data acquisition equipment and diagram of the data acquisition system

4 RESULT

The measurements were carried out continuously during 5 days. The measurement interval for each combination of sensors was set to around 30 seconds. Thus, there were more than 12,000 measurements for each combination of sensors. For long term monitoring, a longer time interval could be set to reduce the calculation cost.

The velocity change of combination S01E02 and S02E06 are presented in Figure 6. The variation of the velocity of these two combinations corresponds well to the temperature change. Higher the temperature, lower the velocity. However, from 28th October, the velocity changes varied significantly although they still follow the same trend as the temperature. During these 5 days, the absolute value of the maximum velocity change is 0.07% which is still relatively small. Normally, the opening of cracks in the vicinity of the sensors appears causes a velocity loss of the order of magnitude 1% (Stähler et al. (2011)). When cracks existed in structure, they will open and close due to the vibration by dynamic load which lead to an unusual behavior of velocity change. Thus, we infer that there is no crack in the middle part of the girder. The bridge is as expected in a good condition.

The correlation coefficient (Figure 6 (b)) which measures the similarity of the signals varied between 1 to 0.994 during the first four days. It dropped to 0.972 rapidly the fifth day mainly due to the big temperature change.



(a) (b)

Figure 6. Velocity change (a) and correlation coefficient (b) of combinations S-E (transmitter-receiver) S01E02 (black), S02E06 (grey) and temperature (silver).

The strain gauges simultaneously measured the distortions related to the passage of traffic but also the thermal factors. The vibration wire gauges used here are not temperature compensated. This type of strain gauges determine strain by measuring the frequency. The frequency should be then transferred to strain by a gauge factor. As this gauge factor is not yet calibrated for Gliwice bridge, only raw frequency data was analyzed. Figure 7 shows the frequency (strain) variations for 5 days. An overall trend is observed in the frequency (strain) values which is mainly caused by temperature variations. Unlike the temperature, after 28th October, the strain also increased significantly as does the velocity change. Both temperature and strain variation were detected by the CWI method.

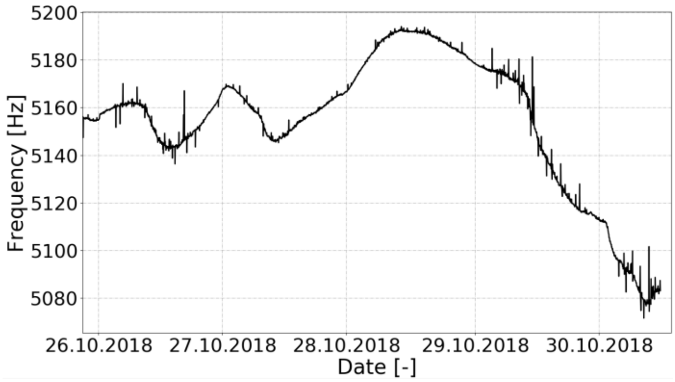


Figure 7. Frequency measured by vibration strain gauges.

5 CONCLUSION

The study shows that transducer SO807 is a very practical sensor for its easy installation, high durability and reliability. All the sensors were installed 4 years ago, and they were still functioning well. Large volume structure can be monitored by limited numbers of sensors. The data acquisition system was reliable; however, the portability and cost of these devices were not ideal enough. Simplification and development of data acquisition system are necessary. The result shows that CWI method has a high sensitivity to detect small temperature induced wave velocity change and strain change in this test. The health condition of bridge could be inferred by the velocity change and correlation coefficient, when the bridge is in good health condition, the influence of the passage of lightweight traffic on velocity change and correlation coefficient is negligible. In conclusion, the CWI method for structural health monitoring in outdoor condition is feasible and it has a cheerful prospect. As a next step, a middle-aged bridge will be monitored and SO807 will be installed in the bridge after its construction with a new method.

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