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Embedded ultrasonic transmission sensors and signal processing techniques for structural change detection in the Gliwice bridge

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Abstract

The present work is a part of a collaborative European funded research project named Infrastar, that aims to deal with advanced monitoring such as load, temperature and strain measurements for fatigue damage assessment in bridges and wind turbines. The main scope of this research is to develop an embedded monitoring system for durability assessment of bridges. The system must interface and integrate the original practice principally based on traditional sensors and combine the response of several diffuse ultrasonic sensors, installed on the structure to monitor the progress of changes, damage with improved realistic degradation models. The system and the embedded sensors were installed to analyze the parameters for the most important material degradation due to operational changes, corrosion of reinforcement, and alkali-silica reaction as well as to detect the abnormal structural nature: static deformation, strain, propagation of crack and transform to safety. The propagation of the several patterns of damage mechanisms can be computed by monitoring the primary environmental parameters of the material (such as thermal load, humidity for the concrete), and key operational parameters (such as strains, deflections, impulse). This paper presents recent advances in bridge structures using embedded monitoring system, which was tested on the real bridge located in Gliwice (Poland). The approach was based on using multiple embedded sensors of different types and based on the obtained measurement signals. The further signal processing was performed using the features of the acquired signals. The applied approach allowed to precisely observe various loading scenarios, which proves its superiority in structural health monitoring. Moreover, the applied sensor network reveals its durability and high measurement precision, which additionally proves the possibility of long-term monitoring of concrete structures.

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1. Introduction

Civil infrastructures, like bridges, are capable of safely transferring the superimposed loads to the foundations; however, their structural integrity is degraded by different kinds of operational and environmental effects. The scheme of the most widespread bridges and their components is presented in Fig. 1. Hence, keeping a high level of structural safety, durability, an efficient system is urgently required for regular structural assessment and performance of the infrastructure. Therefore, the attention in the capability to monitor performance of the large area of structure and detect changes in the structure at the earliest possible stage has increased in the last two decades due to ageing, material degradation and limited budget allocated for maintenance and repair. The system of diagnosis structural integrity and estimate the nature of damage/change in a structure is mostly mentioned as structural health monitoring (Stepinski et al. (2013)).

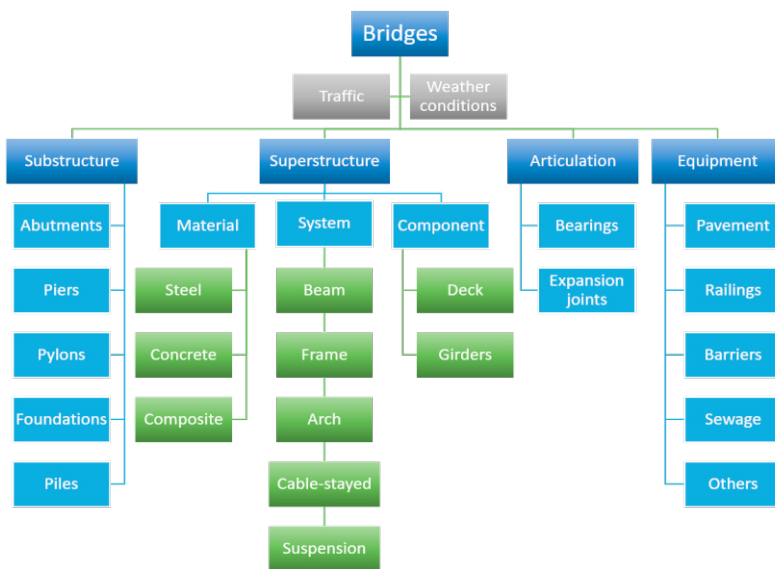


Fig. 1. The scheme of bridge components that are able for structural health monitoring.

Embedded nondestructive testing (ENDT) is an emerging technology that will allow changing the traditional structural health monitoring (SHM) method to an embedded system. It will be the era for embedded SHM such as those imagine for the Integrated Structural Health Management (ISHM) system. ISHM direct to self-acting systems for realizing deleterious changes in the structural material. The embedded sensor is a promising method, which commonly used in other application such as to monitor the degradation of the asphalt layer due to traffic (Miller et al. (2018)). Embedded measurements can be a cost-effective and more user-friendly alternative in comparison to commonly used SHM systems used in civil engineering to detect operational or environmental changes in structure. Embedded ultrasonic transmission can be used as a permanent monitoring system to detect small structural changes in large concrete structures without the necessity of placing a sensor on the spot where the changing is taking place. Once the permanent monitoring system is installed, it has several advantages: to minimize the operating charges of visual inspection and maintenance cost by 25%, and the passage-related costs by 15% by reducing the traffic and range of site examinations, and to minimize the entire life cycle costs of bridges by 10% by using the enhanced prognostic model starting from the design model stage (Bitao et al. (2018)).

Most of the bridge decks are made generally of reinforced concrete. The concrete is a heterogeneous material with non-linear elastic properties. Therefore, material degradation is an important issue with concrete structures. Loads, such as wind, temperature and traffic, could result in progressive and continuous microcracks, which leads to the increased permanent strains and decreased stiffness of the structure. Hence, from the elastic properties of the concrete, we can find the structural changes in the material (Li and Ou (2011)).

The main goal of this study is to transfer the change and degradation detection technologies from the laboratory size specimens to the routine field application. In this research novel ultrasonic transducer developed by Bundesanstalt für Materialforschung und Prüfung (BAM) was used. Its primary part is a hollow piezo ceramic cylinder (Niederleithinger et al. (2015)). These ultrasonic sensors and vibrating wire strain gauge sensors embedded in the bridge located in Gliwice (Poland) during construction in 2015. Since acquired signals from the mentioned ultrasonic sensors are the raw signals, their additional processing is needed. Therefore, the signal processing algorithm is developed for ultrasonic sensors array to detect changes in the reinforced concrete structure and compare the detection capability with traditional strain gauge sensors. These signal processing methods being used for denoising, DC offset compensation, and the feature extraction. The rest of the paper is organized as follows. In Section 2, the test object and experimental setups are described, then signal acquisition is explained. In Section 3, the proposed features are defined. In section 4, the comparison of these features is evaluated and compared with traditional strain gauge sensors. The whole paper is summarized in Section 5.

2. SHM Methodology

2.1. The test object

The Gliwice bridge on the Kłodnica river has great importance in the daily life of the neighboring populations since they ensure vital communication in the highly urbanized Upper Silesia region.

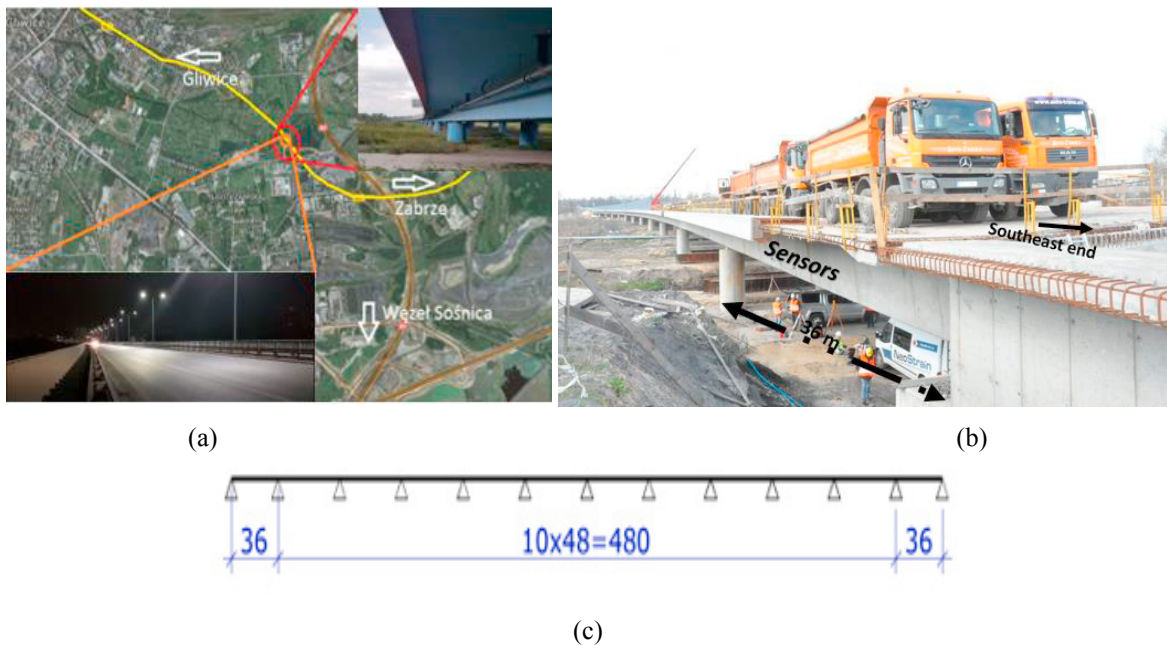


Fig. 2 (a) Location of Gliwice bridges. (b) Monitored bridge span at southeast end. (c) Static scheme of the bridge.

The bridge is located along the Katowice - Gliwice route within Silesian Central Motorway. It was built to overcome an obstacle, which is the Kłodnica river with the flooding area. The location of the bridge is illustrated in Fig. 2a. It consists of twelve-span continuous beam made of prestressed concrete supported by two girders and the total length of the bridge is 552 m (Fig. 2c). There are two steel pot bearings on each support. The 36 meters long span at the southeast end of the bridge (Fig. 2b) was selected as a research object.

2.2. Measuring system

The sensors were installed in the cross-section at the southeast end of the bridge during the erection of the works in 2015. The location of sensors is marked in red and green in Fig. 3. The middle part of the girder was chosen to be monitored, as the biggest stress changes encounter in there. It can be divided into four groups of measurement systems to determine the changes in the superstructure. In the first group, new ultrasonic sensors were mounted in the middle of the span over a length of 4 meters. Each of the eight ultrasonic sensors can work as a transmitter and a receiver.

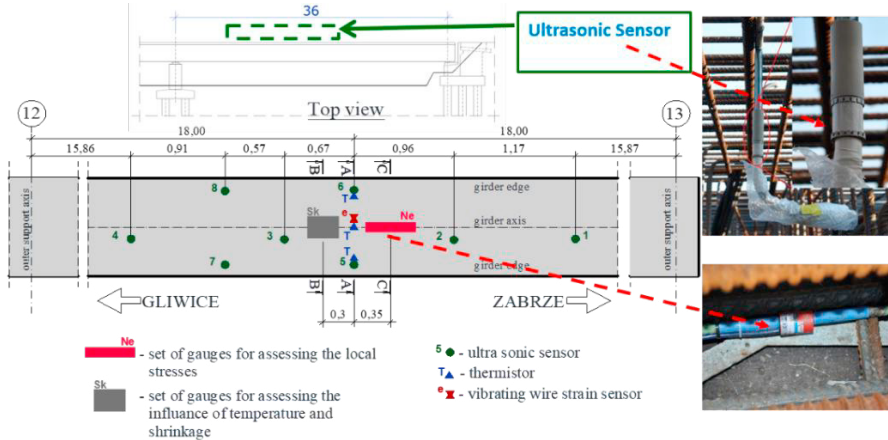


Fig. 3. Arrangement of ultrasonic sensors and strain gauges in the girder.

Fig. 4 shows the exemplary signal (0,0) from pair 1–2 and its spectrum, which is representative of all the signals in duration and bandwidth. The center frequency of the measured signal is around 60 kHz with a sampling frequency of 1 MHz corresponding to the multiple scattering regime. The recorded duration of 5 ms corresponds to about 20 m of travel for this mode, allowing many reflections to occur and resulting in a like diffuse wave. Therefore, the recorded duration is sufficient to acquire most of the reverberating energy. It allows to locate and determine the changes in the structure based on the velocity of the ultrasound wave.

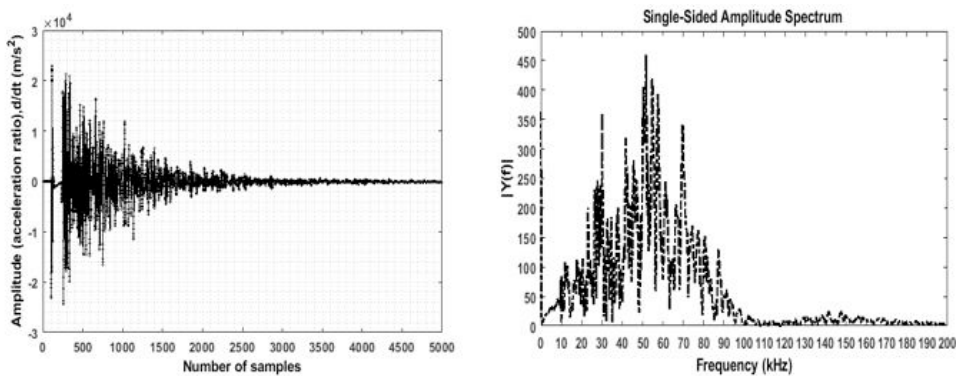


Fig. 4. Diffuse ultrasonic signal and its spectrum.

Three Geokon[®] 4202 sensors were installed in each of the bearing pads. Their purpose is to measure the forces transmitted by the bearing to the concrete of the sub-bearing blow, so they are used to determine the correct operation of the bearing. Six Tascas[®] thermistors and three Geokon[®] 4911 sensors were installed in cross-section A-A (see Fig. 3). The second group, located in the B-B cross-section (see Fig. 3), consists of three Geokon[®] 4202 sensors.

The third group, located in the C-C cross-section (see Fig. 3), consists of three Geokon® 4200 and one Geokon® 4370 sensors. The aim of installing the sensors in these three mentioned cross-sections is to recognize changes and compare with ultrasonic sensor zone.

2.3. Load test and Data acquisition system

The time for the load test was chosen during the night to reduce the influence of the daily traffic. One 382.66 kN truck (5 axials – the values and direction of loading are depicted above the arrows in Fig. 5) was used as a load during the test (Fig. 5). The truck was passing the bridge slowly (10 km/h) and stopped at the southeast end of the bridge near the zone of ultrasonic sensors location (see Fig. 3). This static load took 8 min in the first round and 15 min in the second round. During the examination, the position of trucks was marked according to the zone with ultrasonic sensors. The measurement instruments were placed, and initial readings were made. In this paper, the selected strain gauges (section C-C) and one pair of ultrasonic (S01E02) sensors were chosen and acquired signals were processed to determine the changes and measure strains in girder.



Fig. 5. Truck (5 axials) used for load test.

The data is collected by connecting the computer directly to the Campbell Scientific® data logger and customized data acquisition system for ultrasonic sensors. The data logger has 8 channels (see Fig. 6A). The acquisition from vibrating wire strain gauges was made automatically in every 200 ms and stored in the computer hard disk drive. For ultrasonic measurement, the data acquisition system contains with multi-channel data acquisition module which is connected with the amplifier and the pre-amplifier to amplify the input, and output then filter the signals (see Fig. 6B). In the laptop, custom software is installed to configure and control the measurement system and store the signals. However, the acquisition of the ultrasonic signal was made two times a minute and stored in the laptop.

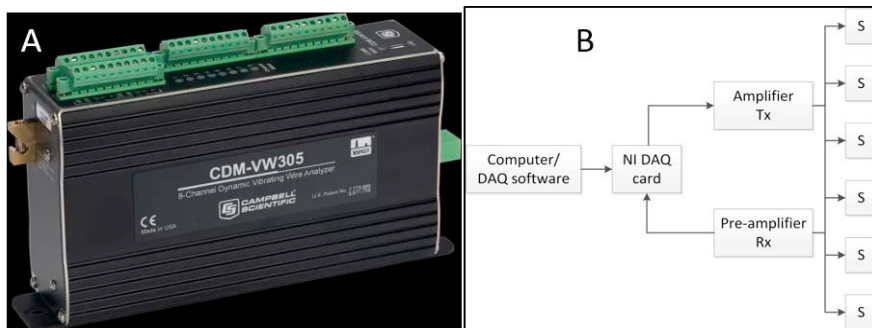


Fig. 6. (a) Campbell Scientific data logger. (b) Data acquisition block diagram of the ultrasonic system.

3. Ultrasonic Evaluation Method

3.1. Feature Extraction

The feature extraction process involves the extraction of load/crack sensitive features from the data collected during the data acquisition procedure to determine the presence of changes in the structure. The feature extraction process is done by using signal processing techniques to sensor data, which involve the processes of data normalization, feature extraction. Data normalization minimized the sensitivity to environmental variability such as temperature fluctuations. The applied signal processing techniques include time domain, and time-frequency domain techniques, their description is presented below.

The window-based cross-correlation is the basis to identify relevance between non-scattered (reference) and scattered signals in the window. The correlation is often obtained in the form of a correlation coefficient (ρ_{xy}). It can be made in the time domain (Poupinet et al. (1996)). It is used to compute the degree of similarity of two signals in the window. The comparison of two signals ($X(t_0)$ and $Y(t_i)$) is performed by the computation in the time window, where $\sigma_{xx}(t)$ and $\sigma_{yy}(t)$ as the standard deviations of two signal, and $\sigma_{xy}(t)$ as the signals covariance. The feature proposed here is the degradation in correlation coefficient given by formula:

$$D_{cc} = 1 - \frac{\sigma_{xy}(t)}{\sqrt{\sigma_{xx}(t) \sigma_{yy}(t)}}, \quad (1)$$

The autoregressive (AR) model can be used as a changes/damage feature extractor for the ultrasonic test. This AR model approach consists of using the parameters (α_i) estimated from the baseline conditions and calculating the response of data obtained from the structure (Chakraborty and Katunin (2019)). This AR residual error ($\varepsilon(t)$) can be written as:

$$\varepsilon(t) = Y(t) - \sum_{i=1}^n \alpha_i \bar{X}(t-i) + e_m, \quad (3)$$

The RMSE (Root Mean Square Error) is an estimator of the overall deviations between the baseline signal and measured signals from the structure. Here, signals are scaled so that the MSE is not sensitive to absolute amplitude differences, where $X(t)$ is a reference signal at discrete time index t , and $Y(t)$ is monitored signal.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Y(t-i) - X(t))^2}{n}}, \quad (4)$$

The curve length related to the change in the smooth signal (curve). Supposing signal as a curve, then signal length consider the change in the complexity of the signal time histories (measured - reference). This feature is a residual of measured to reference the complexity of the signal (Livings (2017)). The differential curve length (DCL) is given in discrete time as:

$$DCL = \sum_{i=1}^n |(Y(t_i) - X(t_i)) - (Y(t_{i-1}) - X(t_{i-1}))|, \quad (5)$$

4. Results and discussion

In order to evaluate the performance and overall response of the integrated system in strain monitoring set of data recorded. The strain gauges simultaneously measured the distortions related to the passage of traffic and mass of truck (load), but also the variations of thermal curvature. In reality, it is difficult to compensate slightly thermal expansion when the temperature increases or decreases sharply. The thermal curvature in the bridge direction is very small, especially as sensors installed inside the girder. Specifically, the thermal curvature mostly changes within 1°C, which requires a longer period. However, the load test was for one hour, which has less effect on the area of vibrating wire-gauge strain time histories. Through the experiment calibration, we find that the strains vary 2 $\mu\epsilon$ /°C. Fortunately, it

is easy to dissociate the deformations related to the temperature or the traffic-induced distortions, due to the fact that the effects of traffic occur at frequencies much higher than temperature variations. Fig.7 (A), (B) shows a realization of the strain time series monitored at vibrating wire strain gauges on during the tests performed in 2018. An overall trend is observed in the strain values, which is mainly caused by the mass of the truck. The results obtained, indicated that the recorded data clearly indicating the strain levels developed due to tension and compression of the live traffic and mass of the truck (load). Fig.7 (C) shows a percentage of the changes in strain due to traffic load and mass of the truck load used for the load test.

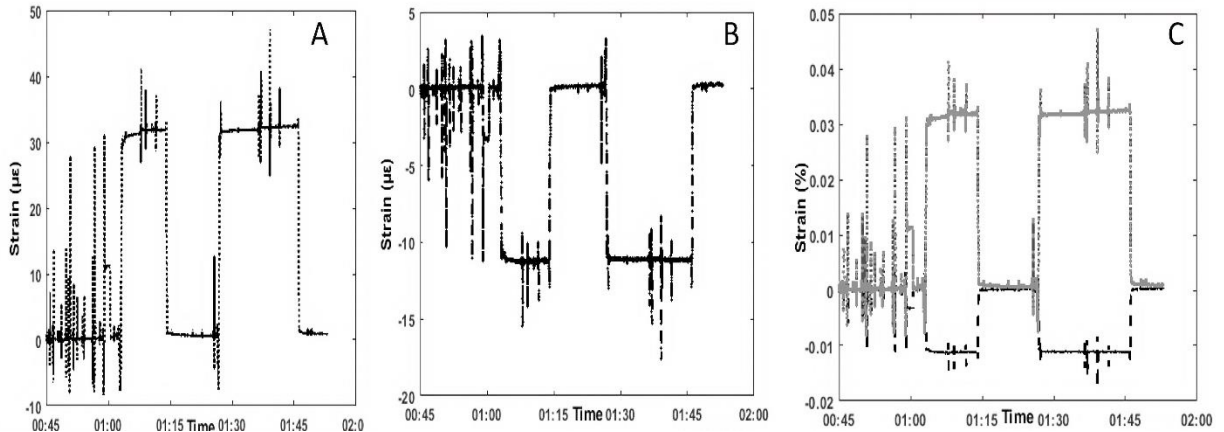


Fig. 7. Strain changes measured by vibrating wire strain gauges.

The ultrasonic features from the combination S01E02 are presented in Fig. 8. The variation of the velocity of these combinations corresponds well to the mass of the truck. Higher the mass, the higher the velocity (acoustoelastic effect). The degradation in correlation coefficient and AR coefficient can separate the load from the live traffic. The correlation coefficient is increasing up to a maximum value when the static load is applied for 15 minutes (second round) on top of the sensor pair S01 and R02 (time 1:30 < t < 1:43). The velocity changes varied significantly although they still follow the same trend as the traditional strain gauges. However, MSE and DCL features values in Fig. 9 give us misleading information and it is difficult to separate the load from traffic. Since, in real structure, acquired signals are very complex, advanced signal processing is important to extract features from them. However, it can be sensitive to detect environmental related changes in the structure, therefore extract more features could be beneficial. During these load test, the value of the maximum velocity changes corresponded to coefficient (D_{cc} , AR) is 0.03 which is still relatively small and comparable with percentage of strain measured by vibrating wire strain gauges (see Fig. 7C). Normally, the opening or appear of cracks in the neighborhood of the sensors causes an unusual behavior in coefficients. Since the Gliwice bridge is five-year-old, therefore from the design model, we can also ensure our result.

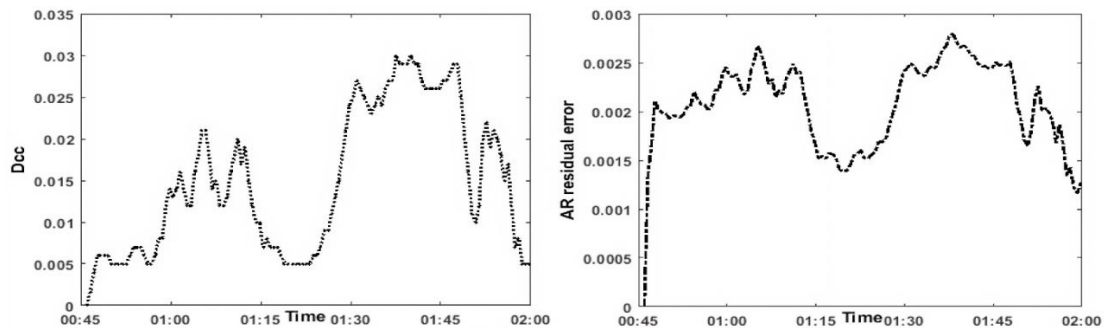


Fig. 8. Values of the feature D_{cc} and AR residual error from transducer pair (S01R02).

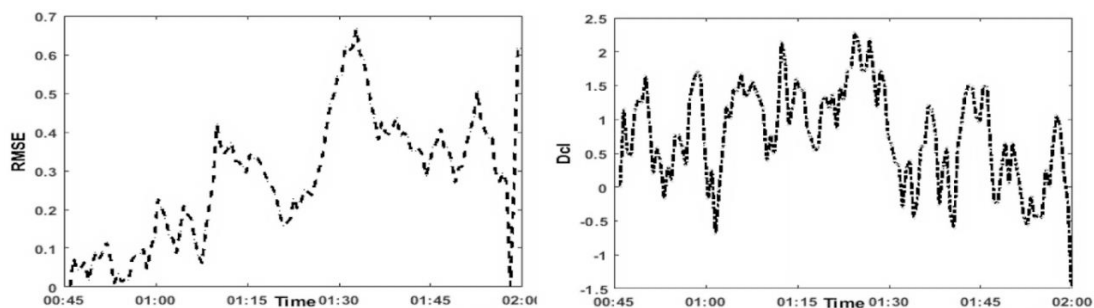


Fig. 9. Values of the feature MSE and Dcl from transducer pair (S01R02).

5. Conclusion

The study shows that applied embedded sensors together with proposed signal processing algorithms can detect the changes in concrete structures as good as traditional strain gauge sensors. An integrated monitoring system - includes traditional gauges and novel ultrasonic measurements are presented. The health condition of a bridge could be guessed by the correlation coefficient and AR coefficient features. Degradation in correlation coefficient and AR residual error appears to be the potential changes/damage-sensitive features (Ultrasonic measurements). The origin of changes in the structure seems to induce variations in correlation coefficient and AR parameter related to the level of changes in the structure. Load changes can be detected and localized and, therefore, this feature can also be used to evaluate the severity of the damage. One can see, the influence of a load of the truck (with lightweight traffic) on AR coefficient and the correlation coefficient is negligible that indicate the good health condition of bridge. The embedded ultrasonic transducers are very practical in the concrete structure, have shown to be valuable sensors for various tasks in long-term SHM for its easy installation, and high durability. In further studies, we take into consideration an automatic change detection application and the comparison of these features will be evaluated using receiver operating characteristic (ROC) curves.

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