Monitoring of oscillations and frequency analysis of the railway bridge "Sava" using robotic total station

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Abstract. Bridges as a civil engineering objects are critical components of infrastructural system of every country. In order to verify design prediction and capability of taking over the design load, bridges are subjected to load testing, during which intentionally provoked displacements are measured. This paper presents implementation of surveying methods in dynamic testing of the railway bridge "Sava" after reconstruction. Bridge "Sava” is a double-track railway bridge over the river Sava in Zagreb. The bridge is a steel structure with total length of 306 m and width of 9.6 m. It consists of 4 spans, 135.54 m long main arch span and three girder spans 57.50 m, 57.96 m and 55.00 m. During the testing bridge was excited by two trains passing at speeds from 20 to 75 km/h. Vibration of the bridge was measured by accelerometers at 42 measuring points and by two models of robotic total station with measuring frequency 10 Hz and 20 Hz at measuring point placed in quarter of main span.

This paper is focusing on the ability of total stations to measure the vibrations to the order of a few millimeters, as well as determining the natural frequencies of the bridge. Measurement results are compared to theoretical results, obtained from numerical model of the bridge and to result of Operational Modal Analysis based on acceleration measurements.

Keywords. Robotic total station, dynamic displacements, vibrations, natural frequencies of the bridge.

1 Introduction

Bridges as a civil engineering objects are critical components of infrastructural system of every country. Every damage or significant deformation affects their performance and safety and eventually it can lead to elimination from the traffic resulting in partial or total collapse of the traffic system. Intensified control of these objects is recommended and necessary in order to achieve their sustainable performance and can be found in Paar (2010). Measurement of displacements and strain can provide early warnings in case of unpredictable damage and stability problems and can also be used for verifying new design solutions.

In order to verify design and capability of taking over the design load, bridges are subjected to load testing, during which intentionally provoked displacements are measured. According to Croatian legislation every railway bridge with a span longer than 10 m has to be tested before opening to traffic. Generally, load testing of bridges consists of static and dynamic tests. For static load testing depending on the characteristics of the tested bridge and expected values of displacements, precise levels, total stations and Global Navigation Satellite Systems-GNSS instruments are mostly used, see Kapović et al. (2005) and Kovačič and Kamnik (2007). Yet, these instruments were not used for dynamic testing of the bridges due to their limitations in sampling frequency and precision. In the past years, GNSS instruments with sampling frequency 10-20 Hz were generally used for monitoring the dynamic displacements of large and flexible bridges in exploitation, see Roberts et al. (2004), Li (2004) and Ogaja et al. (2007). Main limitation for implementation of RTS was the insufficient sampling frequency which was 1 Hz, see Cosser et al. (2003) and limitations regarding the optimal operational range of the RTS which is currently a few hundred meters. The newer models of RTS can precisely measure the position of the moving point with mounted reflector on it, with sampling frequency up to 20 Hz, see Stempfhuber (2009). Another advantage of RTS is the possibility of recording 3D coordinates of a moving target with a millimeter level precision. GNSS instruments have certain limitations for railway bridge monitoring were the passing trains deform or even disrupt the satellite signal, see Wieser and Brunner (2002), Psimoulis and Stiros (2013) for more details. In these situations RTS could be used as an alternative instrument. To date, however, there have been only a few researches in which RTS instruments (with sampling frequency 5-7 Hz) were used for measuring simulated and actual dynamic displacements of bridges, see Psimoulis and Stiros (2007, 2013), Gikas and Daskalakis (2006, 2008), Palazzo et al. (2006) and Lekidis et al. (2005).

This paper brings the possibilities and the implementation of RTS in dynamic testing of the Railway bridge "Sava" during the load testing following its reconstruction. The Railway bridge "Sava" is a double-track railway bridge over the river Sava in Zagreb. During the testing, the bridge was excited by two trains passing at various speeds. Dynamic displacements of the bridge were measured by accelerometers at 42 measuring points (Figure 4) and by two models of RTS with sampling frequencies of 10 Hz and 20 Hz at measuring point placed in quarter of the main span.

The paper is focusing on the ability of RTS to measure the bridge dynamic displacements within the range of a few millimeters and efficiency in identification of the bridge natural frequencies from measured dynamic displacements. Measured results are compared to theoretical results, obtained from the numerical model of the bridge. They are also compared with the results of Operational Modal Analysis based on acceleration measurements.

2 Railway bridge "Sava"

The Railway bridge "Sava" is a double-track railway bridge over the river Sava in Zagreb. The bridge is a steel structure over 4 spans with total length of 306 m and width of 9.6 m. Static system of the bridge is a simply supported continuous beam which is strengthened by the arch in the main span (Langer beam). The main span is 135.54 m long, the remaining three spans being 57.50 m, 57.96 m and 55.00 m long (Figure 1). In order to increase bridge classification to category D4 (mass per axle of 22.5 t, and mass per unit length of 8.0 t/m) strengthening of the bridge had to be performed.

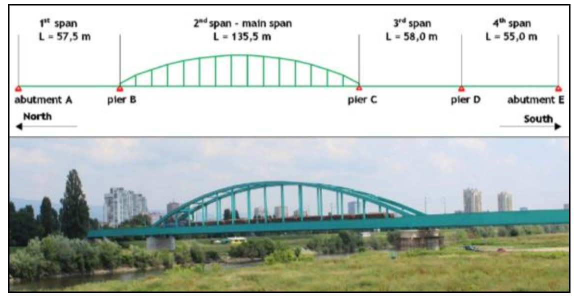

Fig. 1. Railway bridge "Sava".

Repair works were made by incorporating additional elements, existing elements were not removed nor weakened, while all connections were made using rivets or high strength bolts. Pier C was strengthened by additional piles, head beams and new reinforced concrete layer around the existing pier.

2.1 Load testing of the Railway bridge "Sava"

Detailed testing of the bridge was conducted after its reconstruction. Croatian National Standard HRN U.M1.046 requires a load testing to be done after reconstruction is completed and prior to opening to traffic. The purpose of load testing is to empirically quantify the load bearing capacity of the structure, i.e. to verify the theoretical hypotheses on the behavior of the structure. The load testing consists of static and dynamic testing. Field measurements were made on June 7th 2015.

Static and dynamic loading were performed using two 119.5 m long train compositions, each consisting of a locomotive and 8 freight wagons. Mass of the locomotives was 80.0 t (4 axles, 20.0 t per axle) and they were 15.5 m long. Wagons were loaded with gravel, their average mass was 79.8 t (4 axles, 19.95 t per axle) and their length was 13.0 m. Total weight per train composition was approximately 720 t, i.e. 1440 t two trains together.
During the static testing trains were positioned in different locations on the bridge in order to achieve maximum inner forces and displacements corresponding to those from the bridge design. Static testing was carried out through 22 phases of loading and unloading. During these phases displacements were measured by RTS at total of 30 measuring points shown in Figure 2, 9 on east side (P1, P3, P5, P9, P13, P15, P17, P19, P21), and 21 on west side (P1-P21).

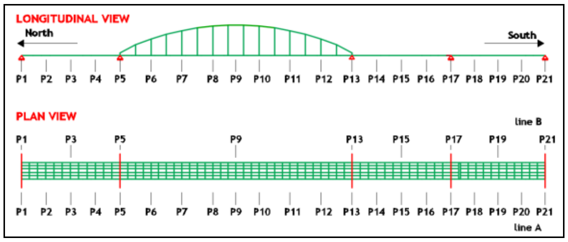

Fig. 2 Measuring points of static vertical displacements.

The same trains were used for the dynamic testing of the bridge. The bridge was excited by two trains simultaneously passing at different speeds (maximum speed was 75 km/h). In this paper, results of two train passages over the bridge are presented. In first event, two trains were passing over the bridge simultaneously (parallel at two tracks) at speed of 20 km/h. In second event, the passage of two trains was not simultaneous. The train on the east track passed over the bridge with a delay of approximately 9 s to train on the west track, because it accelerated slower than the train on the west track. It resulted in 187 m distance difference at the speed of 75 km/h. This can be seen in measured vertical displacements of the bridge, i.e. responses from the bridge in Figure 6.

The main focus of this research was to evaluate the ability of RTS to measure the dynamic displacements to the order of a few millimeters, as well as determining the natural frequencies of the bridge. For this purpose during dynamic testing, in addition to conventional measurement of vibrations by accelerometers, displacements of the bridge were measured by two models of RTS with sampling frequencies of 10 Hz and 20 Hz. RTS measuring point was placed in quarter of the main span (Figure 3).

Fig. 3 Position of RTS instruments and reflector.

Both RTS were set on the stable ground at a distance of 60 m from the measuring point (reflector). The reflector was fixed on the main girder in quarter of the main span from the south-west side of the bridge, and is shown in Figure 3.

Dynamic components of displacements were determined from measurements performed by accelerometers, while RTS measurements provided both, semi static and dynamic components of displacements during the passing of trains.

Additionally, modal parameters of the bridge (natural frequencies, modal shapes and damping ratios) were determined using Operational Modal Anallysis (OMA). During implementation of OMA, accelerations were measured at 42 points, during ambient excitation. Positions of acceleration measuring points (1-42) and RTS are shown in figure 4.

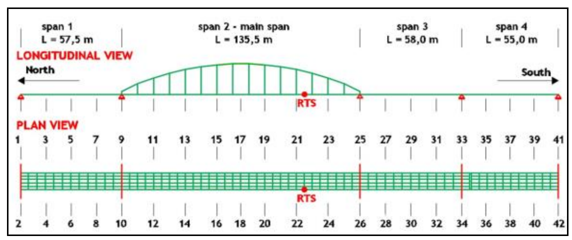

Fig. 4 Position of accelerometers and RTS measuring points.

3 Field measurements during load testing of the bridge

Modal parameters of the bridge were determined using Operational Modal Anallysis (OMA). Two models of RTS used for static load testing of the bridge, were used during dynamic load testing to test their possibilities for monitoring of dynamic displacements of structures. Since the performance of RTS for kinematic measurements is affected by numerious factors and depends on the characteristics of the RTS, the type of used reflector and atmospheric conditions during the measurement, Gikas and Daskalakis (2006), Zarikas et al. (2013), in this research both RTS models were used to measure coordinates of the same reflector. This way, we managed to get an extra set of measurements which allowed us to compare obtained results from two models of RTS instruments. Two models of RTS that were used are Leica TPS1201 with sampling frequency up to 10 Hz and Trimble S8 with sampling frequency up to 20 Hz, see Figure 5.

Sampling frequency of Leica TPS 1201 set up to 10 Hz was not achieved and varied around 7 Hz with irregular time intervals between individual records, found in Stiros et al. (2008), Marendić et al. (2013). In order to increase the number of recorded measurements, Visual Basic (VB) application that relies on GEOCOM protocol was used. The VB application controls the RTS measuring process via laptop and enables to record 12 to 13 measurements per second. In order to record 20 measurements per second, robotic total station Trimble S8 was used and was also controlled by laptop with Trimble PC software installed. Trimble S8 achieved declared sampling frequency of 20 Hz.

Fig. 5 Leica TPS 1201 and Trimble S8.

3.1 Analysis of results

The first step of data processing was to transform determined coordinates of the moving target into a local Cartesian coordinate system with the origin in the center of the reflector and one axis parallel to the direction of the bridge. This allowed analysis of the displacements of the reflector along the longitudinal, lateral and vertical axis of the bridge. The next step of analysis was to identify the exact moment of the trains entering and exiting the bridge. These moments were identified in the field by the RTS instrument clocks, and are shown in Figures 6 and 9 by vertical dashed lines. Figure 6 summarize vertical displacements measured at the quarter of the main span for events 1 and 2. Event 1 shows two trains simultaneously passing from south to north at speed of 20 km/h and event 2 shows two trains passing from south to north at speed of 75 km/h with time delay of 9 s between trains (with distance difference of 187 m). In these figures displacements measured by both RTS models are presented, model 1 presenting Leica TPS 1201 and model 2 presenting Trimble S8.

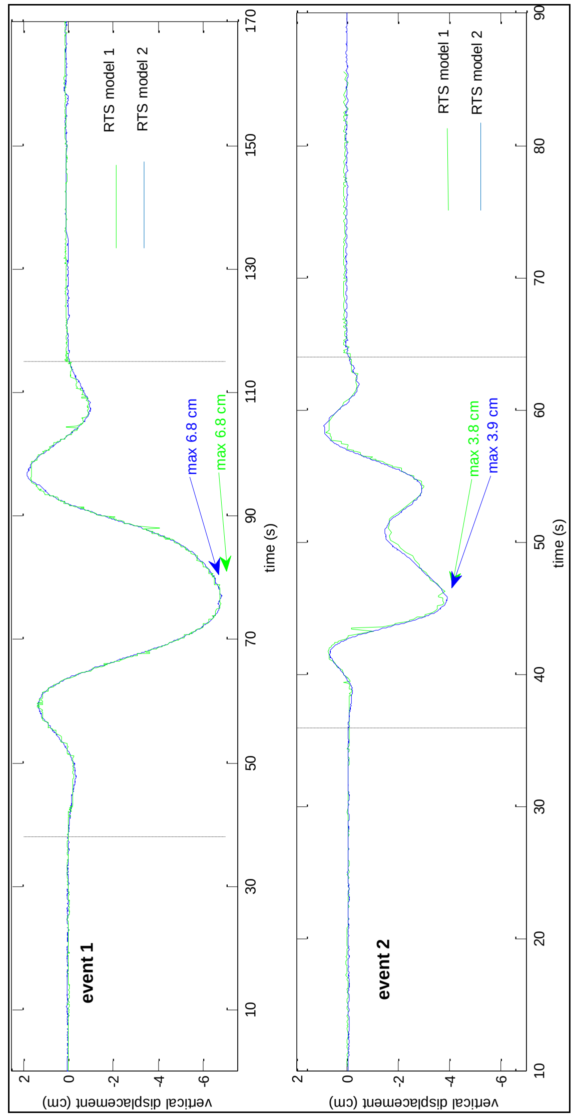

Fig. 6 Measured vertical displacements of the bridge determined in events 1 and 2.

The vertical vibrations of the bridge during its excitation by the passing trains can be analyzed into a long-period and a short-period component, corresponding to the semi-static and dynamic displacements, for more details see Psimoulis and Stiros (2007), and Moschas and Stiros (2011). Figure 7 shows semi-static displacements of the bridge determined by both RTS models for events 1 and 2. The semi static displacement component was extracted using the Moving Average (MA) filter, Moschas and Stiros (2013).

As we can see from the figure 7, two models of RTS determined almost the same values of displacements. Maximal vertical displacements measured in event 1 by booth RTS models were 6.8 cm. Maximal uplifting was measured at the time when two trains were in the first span of the bridge (1.7 cm - RTS Model 1 and 1.8 cm - RTS Model 2). Maximal vertical displacements measured in event 2 by booth RTS models were 3.8 cm and 3.9 cm and maximal uplifting of 0.7 cm and 0.9 cm were detected. Lower displacements measured during event 2 were caused by the time delay and distance difference of two trains passing over the bridge. Differences of measured vertical displacements by two RTS models were within the range of ± 2.2 mm (Figure 7).

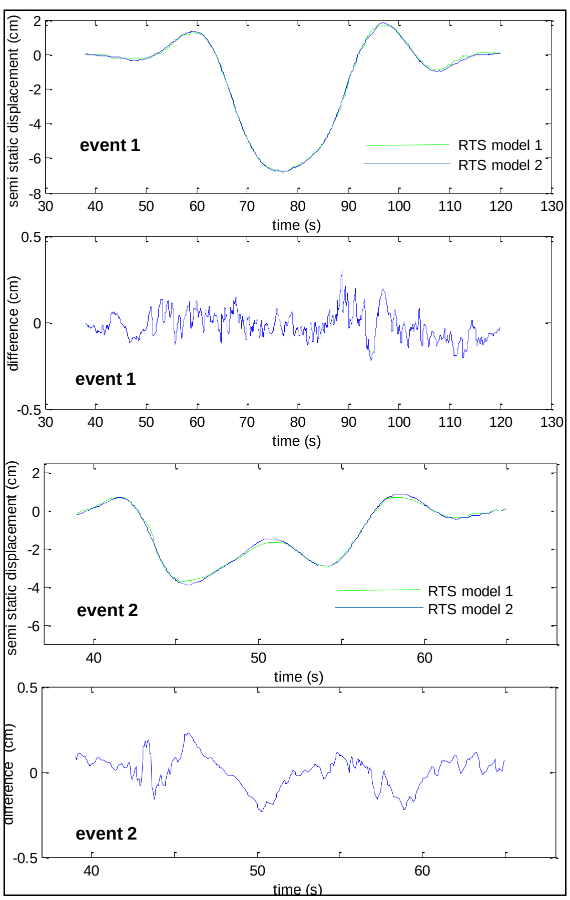

Fig. 7 Semi static displacement determined by both RTS models and their difference

Values of horizontal displacements of the bridge in longitudinal and lateral axis of the bridge were significantly smaller than vertical displacements and they were in the range of a few millimeters. From the recorded data prior to passing of the train when no train was in the vicinity of the bridge and no movement was expected (except of small-scale oscillations of the bridge induced by the environment conditions), the noise level of measurements was estimated based on the amplitude of the measured displacements (figure 8).

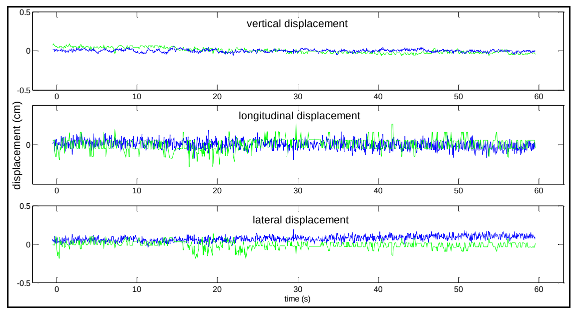

Fig. 8 Measured displacements of the bridge when trains were not passing across the bridge

Recorded displacements along the vertical axe during 60 seconds long period are within ±0.8 mm wide interval by booth RTS. Recorded lateral and longitudinal displacements by RTS Model 1 are within ±1.7 mm and ±2.4 mm and by RTS Model 2 are within ±1.1 mm and ±1.4 mm.

Measured horizontal displacements of the bridge in longitudinal and lateral axis of the bridge in the events 1 and 2 are shown in Figure 9. In time interval when the trains were passing across the bridge (time interval between vertical lines on the figure 9), actual displacements are clearly distinguishable from the noise level in measurements for both events in longitudinal and lateral direction.

Maximal longitudinal displacements of the bridge during events 1 and 2 by RTS Model 1 and 2 were 0.7 cm and 0.4 cm. Maximal displacement measured in lateral direction were 0.4 cm and 0.7 cm. Since all displacements were measured when trains were passing over the bridge, they indicate the real motion of the bridge caused by train's passage.

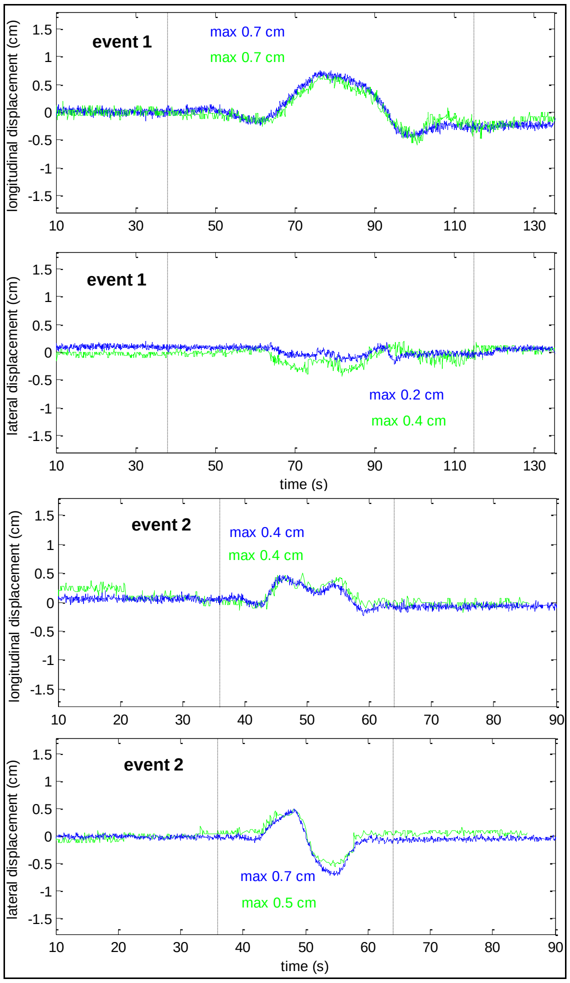

Fig. 9 Measured horizontal displacements of the bridge determined in events 1 and 2.

As it can be seen from the measurements results, both models of RTS measured the response of the bridge to the passing trains and showed the ability to record dynamic displacements of the bridge which are in the range of a few millimeters (horizontal displacements of the bridge).

3.2 Identification of natural frequencies of the bridge

The next stage of data processing involves computation of the natural frequencies of the bridge from displacements measured by RTS. Fast Fourier Transform (FFT) analysis was used to convert the time domain records of displacement measured by RTS to frequency domain. Natural frequencies were identified as resonance peaks of these spectral functions. Figure 10 shows the spectral function determined from vertical and lateral displacements measured by RTS (Model 2) during event 2. Data recorded in conditions of free oscillation of the bridge, after the train passing across the main span, were used for this analysis. Natural frequencies at 1.563 Hz and 2.969 Hz were identified from the recorded vertical displacements, while natural frequencies at 1.015 Hz, 1.953 Hz and 2.734 Hz were identified from the lateral displacements.

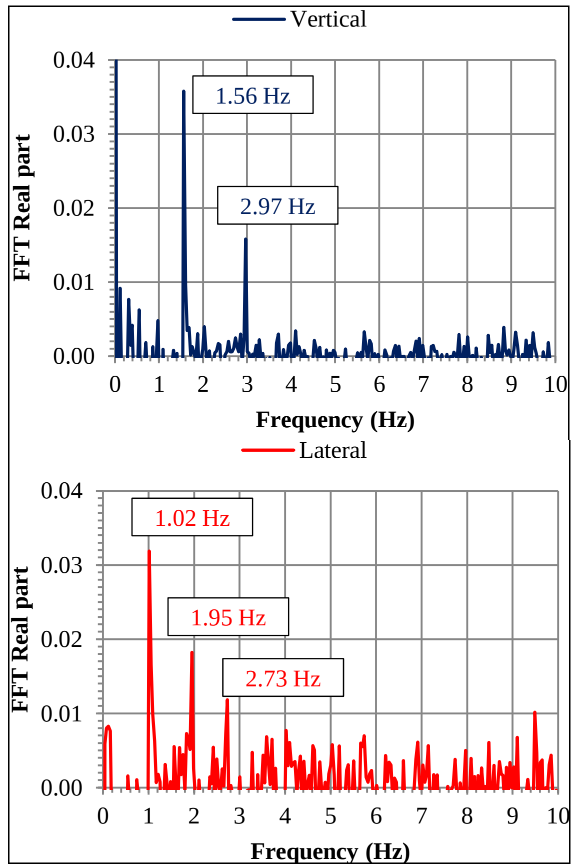

Fig. 10 Spectral functions determined from RTS measurement and identified natural frequencies in vertical direction and lateral direction.

Natural frequencies determined from RTS measurements were directly compared to those determined by OMA and to the numerical natural frequencies determined from FE model of the bridge. OMA uses ambient environmental and traffic excitation, whereas for the identification of natural frequencies, modal shapes and damping ratios methods of frequency domain decomposition

(FDD) were used in this research. The procedure is based on singular value decomposition (SVD) of power spectral density (PSD) matrix of the measured responses, see Brincker et al. (2001). Since 42 measuring points were used, we can conclude that this technique gives reliable results.

Comparison of natural frequencies determined experimentally from RTS measurements, from OMA and numerical natural frequencies is given in table 1.

Table 1. Determined natural frequencies of the bridge

Experimental frequency ± st. dev. - OMA [Hz]	Numerical frequency [Hz]	Experimental frequency RTS – event 2 [Hz]
1.01 ± 0.010	1.03	1.02
1.57 ± 0.064	1.63	1.56
1.96 ± 0.009	1.54	1.95
2.73 ± 0.034	2.81	2.73
2.98 ± 0.043	3.11	2.97

Presented results show excellent agreement between natural frequencies determined experimentally by OMA and those determined from RTS measurements. Results of numerical frequencies determined from FE model show some discrepancies when compared to ones determined experimentally. Accuracy of FE model is influenced by input parameters such as material properties, geometry and boundary conditions that are often not comprehended with sufficient accuracy.

4. Conclusion

The paper shows possibilities and implementation of RTS in dynamic testing of the Railway bridge "Sava" after its reconstruction. Two models of RTS were measuring vibrations of the bridge caused by two trains passing at different speeds.

As a response of the bridge to the passing trains, determined vertical displacements of the bridge were up to 6.8 cm. Further, determined horizontal (lateral and longitudinal) displacements were up to 0.7 cm. Differences of measured vertical displacements by two RTS models were within the range of ± 2.2 mm, indicating high measurements precision achieved by RTS running in kinematic measuring mode. RTS showed the ability to record the response of the bridge to passing trains even if displacements are in the range of a few millimeters (horizontal displacements of the bridge) and proved to be useful for dynamic monitoring of structures.

Displacements measured by RTS were converted from time to frequency domain using FFT analysis. First five natural frequencies of the bridge were identified. Natural frequencies at 1.56 Hz and 2.97 Hz were identified from vertical displacements, and those at 1.02 Hz, 1.95 Hz and 2.73 Hz were identified from lateral displacements. Natural frequencies determined from RTS measurement show excellent agreement with natural frequencies determined experimentally by OMA. These results also confirmed precision of RTS measurements, since the natural frequencies of the bridge were determined from the RTS measurements of free oscillations after the passing of the trains across the main span and values of measured displacements were being within the range of 1-2 mm.

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