Monitoring of the static and dynamic displacements of railway bridges with the use of the total station and set of the electronic devices

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ABSTRACT

In the case of monitoring of bridges, the determination of vertical displacements is one of the most important issues. New measuring system was developed and implemented to assess the technical condition of railway bridges and viaducts based on measurements of the construction response to passing trains. The system uses inertial sensors: inclinometers and accelerometers, which do not need any referential points. During the passage of a train all the signals from the sensors are registered by a central unit and then sent to a server via Internet. Measured values of displacements and accelerations are compared with the results of the model analysis, which allows the assessment of the current condition of the bridge. Static displacements referenced to the external coordinate system are measured independently at a certain time interval using Total Station. An automatic mode of measurement to the group of prisms installed on the bridge was used in presented project. Three fixed points has been marked as a reference – one of them serves as a directional and refractive point. Based on observations to this distant point, a temporary refraction was taken into account in calculations of displacements. The tests were carried out on a viaduct along high-speed railway line. Results of tachymetric surveys were compared to readings of static component from inclinometers measured before entering the train. Analyzes were conducted on the possibility of the use of inclinometers to static displacement measurements.

I. INTRODUCTION

Structural monitoring is currently gaining importance in engineering practice in connection with the need to assess the stability of objects exposed to external factors: geological and hydrological phenomena such as earthquakes (Suzuki et al., 2007), climatic cataclysms (Cheung et al., 2010), extreme snow- and rainfall (Bossi et al., 2015) or human intervention (Bętkowski et al., 2014), mainly in connection with the implementation of new investments. The main advantage of monitoring is a quick response to ongoing destructive processes, thanks to which warning, preventive or protective actions may be taken.

In the early stage of monitoring development, geodetic measurement techniques had long been used to study movements and deformations of objects. For detecting vertical displacements, geometric leveling was mainly applied and for horizontal ones – angular techniques. Thanks to the development of technology and engineering concepts, geodetic methods have been enriched with very precise distance measurements (Ehrhart and Lienhart, 2015; Parker, 2017); there was also the development of automation of measurements and calculations. This led the acceleration of surveing procedures, and thus – shortening the time between the moment the measurement was performed and the delivery of its results for the purpose of the inference. As a result, it became possible to perform quasi-continuous measurements, which became a source of inspiration for the implementation of the monitoring idea. A significant contribution to the development of monitoring had the GNSS satellite surveying technique, mainly in the RTK (Psimoulis and Stiros, 2008) and PPP methods (Yigit and Gurlek, 2017). Despite their lower accuracy than traditional methods, GNSS surveys have the advantage that they can be used independently of humans in a quasi-continuous manner, with a real frequency of up to 10 Hz.

Finally, the photogrammetric technique is becoming more and more popular. Thanks to the increasing possibilities of digital photography, it is used in situations in which quick, simultaneous measurement must cover a greater number of control points located in different places of the tested object (Feng D. and Feng M., 2016; Sabato and Niezrecki, 2017; Waterfall et al. 2012).

However, in the field of monitoring human invention has exceeded the traditional approach to geodetic methods by including a wide range of sensors. In this way, displacement measurements were enriched using hydrostatic leveling (Shardakov et al., 2016), and in addition, sensors such as inclinometers (Plichta et al., 2013; Olaszek, 2014;) and accelerometers (Mohd et al., 2018) or both of them (Ozdagli et al., 2016) had been introduced. Due to better recording of temperature, pressure and air humidity, it became possible to precisely trace the impact of atmospheric phenomena on the response of monitored objects. There is also continuous miniaturization of sensors and improvement of communication techniques, which opens up new possibilities in the field of monitoring automation (Guidorzi et al., 2014).

Monitoring techniques using inertial sensors are still in development, so at many universities and industrial laboratories works are undertaken to develop competitive monitoring technologies with their use. The Polish scientific and technological consortium led by Road and Bridge Research Institute has attempted to develop its own technology (Olaszek et al., 2017). The first objects of its applications are steel railway bridges. It was assumed that the measuring device will have a compact modular character and will operate autonomously. In order to assess correctness of its operation it was decided to be controlled by tachymetric measurement referenced to independent points located outside the tested object. The new measurement module developed as part of the above-mentioned research project is described and next selected results of its operation are presented. The measurements are supported by independent trigonometric surveys. The course and results of the test will also be presented, the aim of which is to assess the impact of temperature on the behavior of a given bridge structure at diurnal and long-term temperature changes.

II. Description of Monitoring System

A. *Motivation*

One of the most important elements of the developed monitoring system is its innovative solution of indirect measurement of displacements based on measurements using inclinometers and accelerometers. Many researchers carry out work related to the use of detectors for this purpose, which do not require any reference point – which are based on inertia. They present works on using accelerometers to measure both accelerations and displacements of bridges under dynamic loads. A disadvantage of this method is the necessity of double integration of an acceleration signal, which can lead to considerable errors in estimating the displacements. There are various methods suggested to correct those errors (Gindy et al., 2008; Sekiya et al., 2016; Park et al., 2013), but generally it is not possible to accurately estimate the displacements on the basis of accelerations without additional measurements, for example such as strain gauge measurements (Park et al., 2016).

A number of articles related to the use of inclinometers for monitoring automatic displacements of bridge structures were also published. Most of those papers are limited to measurements under static load (Olaszek, 2014). Only few of them present the use of inclinometers to determine deflections during static and dynamic load tests (Hou et al., 2005). Works using inclinometers to determine displacements under dynamic load and high-speed train passages are presented in Hem et al. (2014) or Martí-Vargas (2015).

The new method presented here is based on the integration of the signals from inclinometers and accelerometers. A similar way of integrating the signals from an inclinometer and an accelerometer in order to determine lateral displacements of a railway bridge support is presented by Ozdagli et al. (2016).

B. *Hardware*

The developed prototype of the monitoring system consists of a central unit and measurement modules (Olaszek et al., 2018). Each module contains an 8-channel, 16-bit analog-digital converter adapted to support the following detectors:

- uniaxial gravity inclinometer with measuring range of ±1°;
- triaxial piezoelectric accelerometer with measuring range of ±5g;
- MEMS-type triaxial accelerometer with measuring range of ±3g;
- resistance strain gauge;
- temperature sensor with a measuring range from -55°C to +125 °C.

The central unit which controls the measuring module consist of a microcontroller, local memory on a SD card, a real-time module and a GSM module. Communication with the measuring modules is established by means of RS485 protocol. The system is equipped with an algorithm of detecting trains' passages, thanks to which a loop of data acquisition is fully automated. The signals registered by the sensors during a train passage are sent as a text file to remote FTP server. The system works autonomously and the buffer power supply protects from power failures.

C. *Algorithm and Software*

Inclinometers are installed in one line on a bridge span and accelerometer at the point of displacement examination. The signals from the inclinometers are used to determine the so called quasi-static component of a displacement, and the signal from the accelerometer to determine a dynamic component.

In order to calibrate the inclinometric measurements of vertical displacements with respect to the external coordinate system, an independent trigonometric survey is planned over long intervals. A group of prisms installed on the bridge span is observed using Total Station in serial mode with automatic target recognition. Each measurement consists of three full series with discrepancy control. Measurements are referenced to three fixed points – two close and one distant. The latter serves as a directional and refractive point. The aim of the survey is to determine the vertical deflections of the span. On the basis of a stable refraction point, an angle correction is calculated to minimize the effect of vertical refraction. Corrected and averaged vertical angles and distances are used to calculate displacements of the bridge in places where prisms are located.

The monitoring system measure all signals from the electronic sensors continuously 24h per day. Due to restrictions on the size of data, the system records only the data connected with train passage. The signals registered by the electronic sensors include three parts:

1) 5 second time registration of all signals before the train entry to the bridge;
2) force vibration registration when the train is on the bridge;
3) free vibration registration after train leaves the bridge.

The first part of the inclinometer signal registration (5-second) is used to calculate static displacements. The method of determining the deflection line by means of spline curves is used (Olaszek, 2014). This part of the monitoring procedure is shown on the left side of the block diagram (Figure 1). Displacements are mainly caused by temperature changes (in one day and one year) and can be compared to periodic trigonometric measurements. The all 3 parts of registered signals from inclinometer are used to calculate the quasi static component of dynamic displacement. The quasi static component is calculated based on signals after low pass filtration. The method of determining bridge deflection lines using spline curves is applied also (Olaszek, 2014). The force and free vibration parts of signal from accelerometer are used to calculate the dynamic component of total dynamic displacement. The values of dynamic component are calculated based on accelerometer signal after low and high pass filtration. Next the method of double integration is applied. The total dynamic displacement caused by the train passage throw the bridge is calculated as the sum of the quasi static and the dynamic components. These parts of monitoring activities are presented at the center and right side of the flow-chart (Figure 1). The details of the method of determining displacements will be presented in a separate publication.

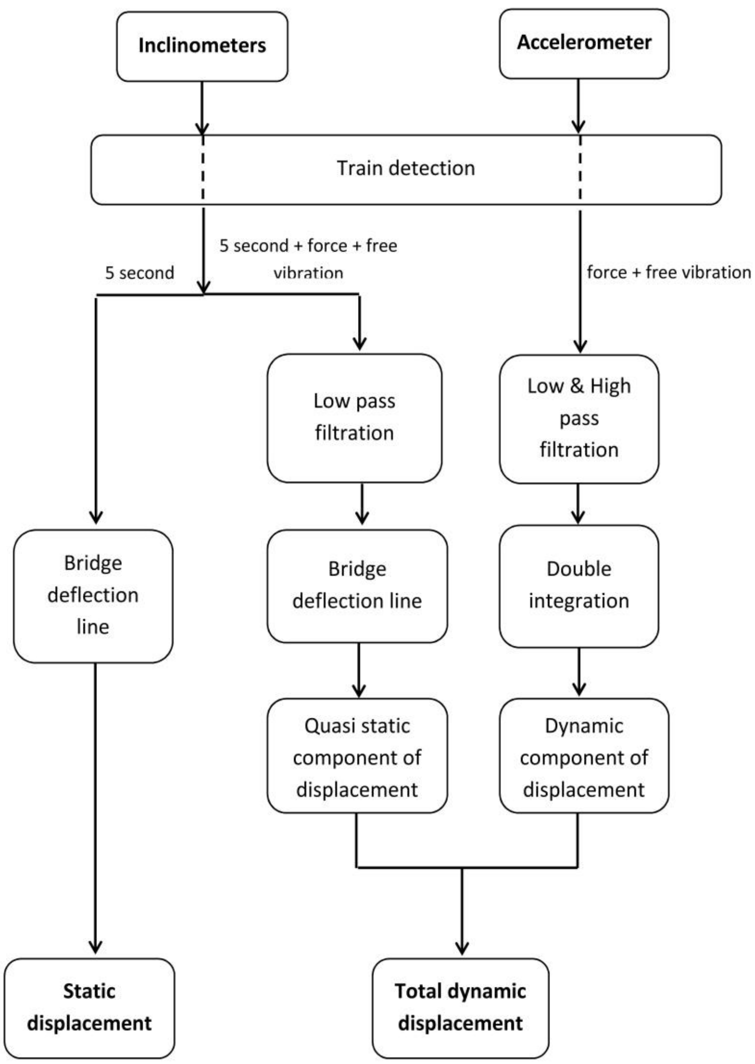

Figure 1. The flow chart of the static and dynamic displacements monitoring

III. First test of the bridge monitoring

A. *The tested bridge*

The system presented herein was implemented on arch bridge located in high speed railway (Fig. 2). The bridge consists of two new steel arch structures (from 2014 and 2015) with span length of 75.00 m. The arch and the arch tie both have box cross-section. The arch ties are suspended at the arches using 13 pairs of steel hangers. The bridge has ballasted deck, cross-bars from double-tee plate girders and reinforced concrete slab floor. The structure was accepted for train speed up to 250 km/h.

In the case of an arch bridge, the extreme deflection appears at about one a quarter of span length. For preliminary testing it was enough to monitor half of the span. Three inclinometers were installed in one line at bridge deck and the accelerometer was located at one a quarter of a span length (Fig. 3).

Trigonometric survey was made using robotic total station Leica TCRP1201+. The instrument was mounted to the bridgehead at one side of the bridge ('TS' in Figure 3) and was oriented parallel to the span. Two reference points were mounted on nearby traction poles and were used to control the position of the instrument. The refraction point was located on the opposite bridgehead. Each point was measured automatically in three series just before and after the train passage.

Due to small distances (up to 80 m) the impact of refraction was corrected with the linear equation: $d\beta = a \cdot \Delta T + b$, where $d\beta$ is the correction of the vertical angle β and ΔT – the difference between the temperature of the air during measurement and the reference temperature.

For the needs of research, all-day observations were made to test the method of taking refraction into account and, independently, assessing changes in deflections of the span as a function of temperature.

For a temperature difference of 20°, the correction factors for the furthest points did not exceed 2 mm. Based on three series of observations, each time an average error of the arithmetic mean was calculated for individual points – it ranged from ±0.1 to ±0.8 mm.

Figure 2. View of the tested bridge

B. *Dynamic displacements results – one train passage*

An example of an analysis of a single registration and indirect determination of displacements is presented in Figure 4. The registration concerned a passenger train passage with the speed of about 150 km/h, consisting of a train ED-250, gross weight 445 tons and length of 187 m (data from the Railway Traffic Management Centre). The first two graphs present signals registered by the inclinometers and accelerometer. Next graph presents the method of integrating the signals from the inclinometers (a quasi-static component of the displacement) and from the accelerometer (a dynamic component). The last graph presents result of an indirect measurement of displacements calculated as the sum of the quasi static and the dynamic component. The measurement error using the indirect method in relation to a reference method did not exceed ±0.4 mm (the relative error 3.4%) for extreme value.

C. *Dynamic displacements results – continuous monitoring*

The installed monitoring system registered data concerned all passing trains from 1st of June 2017 to 31th of May 2018. The comparative tests using inductive transducer were not conducted continuously, it was repeated 7 times. The standard deviation for extreme values of measurements done using the indirect method in relation to a reference method did not exceed ±0.5 mm (average 4%) at the case of the multiple unit trains and not exceed ±1.2 mm (average 6%) at the case of the separate locomotives with train cars.

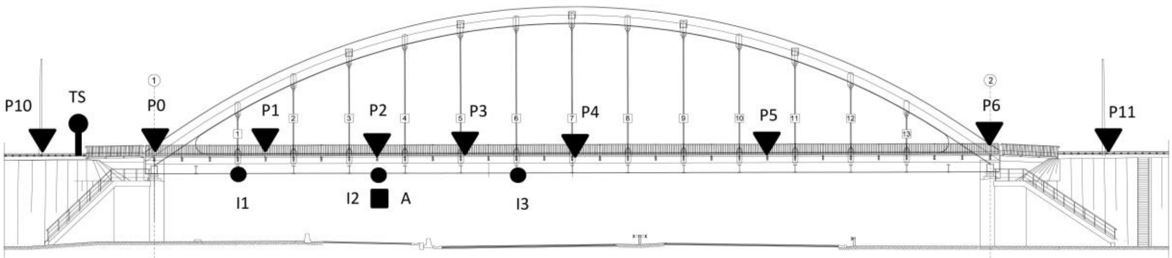

Figure 3. Scheme of inclinometers location (I1, I2, & I3) and accelerometer location (A) for continuous monitoring of the bridge deck; prisms (the measuring: P0 .. P6 and the reference system: P10 & P11, P12 is located outside the drawing); TS – Total Station location

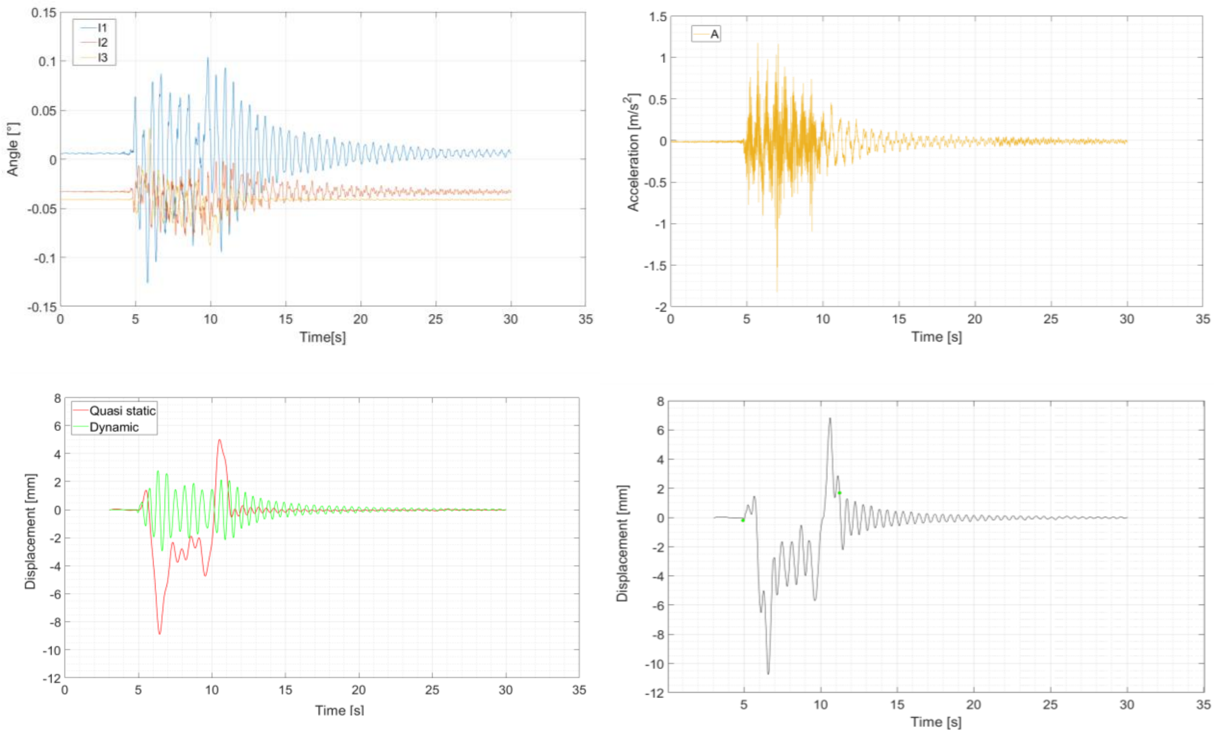

Figure 4. An example of an analysis of a single train passage versus time; top left: signals from inclinometers, top right: a signal from an accelerometer, bottom left: determined quasi-static component (from inclinometers) and dynamic component (from an accelerometer), bottom right: result of dynamic measurement of displacement

Figure 5 shows an example of an analysis of trains monitored for one day. The graph presents determined values of extreme displacements and two most popular kinds of train are marked.

The displacement values determined by the monitoring system were compared with the values determined using the numerical modelling (Olaszek et al. 2017).

D. *Static displacements*

The research aimed at harmonizing the results of Total Station (TS) measurement with displacements calculated on the base of measured inclinations included:

- tachymetric measurement before arrival of the train,
- 5-second inclinometer readings before the train reach the bridge,
- calculation of displacement for both methods and comparison of results.

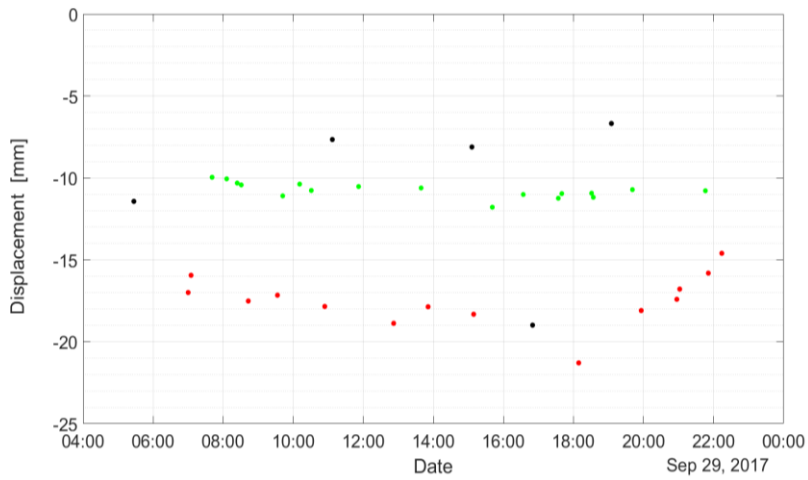

Figure 5. An example of displacement monitoring under load of trains for one day (29th of September): extreme displacement versus time; red dot - locomotive EP09 and passenger railway cars, green dot - train ED-250 (Pendolino), black dot - others trains

Readouts from the TS were initially analyzed for gross errors according to Wójcik et al. (2013). Often, the total station misinterpreted readings to other prisms than it was predefined. In addition, from time to time it recorded observations significantly out of the others. All these cases were considered as outliers and were eliminated from further calculations. The remaining data were averaged and then adjusted due to the vertical displacements detected in the refraction point. Average errors of the measurement were also calculated.

The results from Total Station were compared to the static component from inclinometers measured before the train entry (5 second time registration of all signals before the train entry to the bridge). Analyzes were conducted on the possibility of the use of dynamic inclinometers to measurements of static displacement.

The example of an analysis of static displacements during a one day is presented in Figure 6 and during one year in Figure 7. The one-year registration contains the measurements done before all trains from 12 am to 1 pm every day.

Due to observed local deformations of the bridge deck as a function of temperature, it was not possible to determine static displacements based on the indications of three inclinometers in a manner analogous to determining the quasi static curve described in the point B. The displacement at ¼ span length point was determined based on the readouts of inclinometer No. 1 only.

At the case of one day measurements we can observe here the high compliance between indirect survey of displacement with the use of inclinometer and total station measurements.

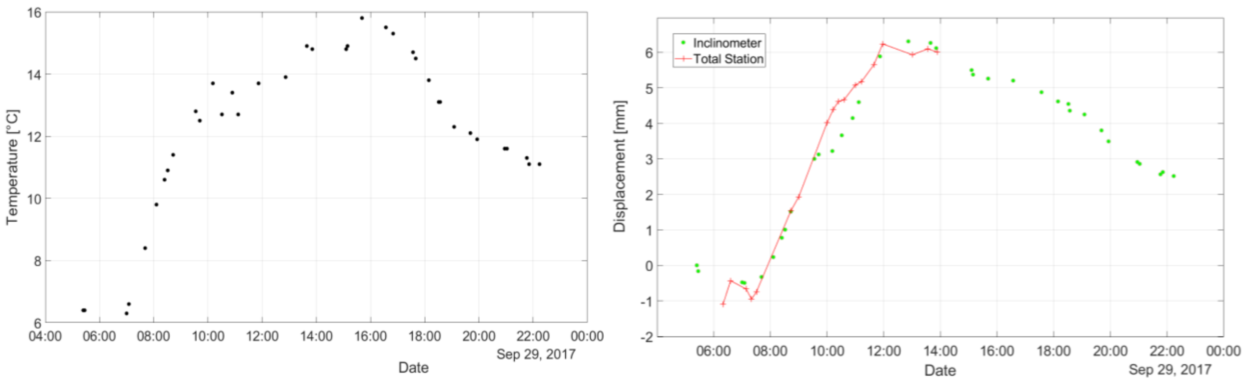

Figure 6. An example of an analysis of a one-day static displacement at ¼ span length point; left: temperature measurements versus time, right: indirect measurements of displacement with the use of inclinometer (green points) and total station measurements of displacement (red line with sharps) versus time

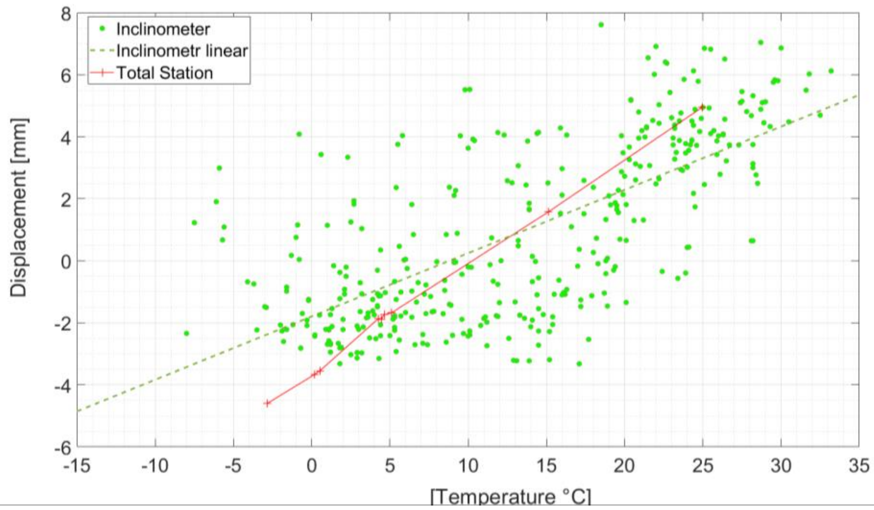

Figure 7. An example of an analysis of a one-year static displacement at ¼ span length point versus temperature; indirect measurements of displacement with the use of inclinometer (green points) with linear fitting (green dashed line) and total station measurements of displacement (red line with sharps)

At the case of one-year indirect measurements of displacement with the use of inclinometer we can observe large dispersion of results versus temperature. After calculating the fitting line from the clouds of inclinometer survey the increase of displacement is equal to 2.0 mm for 10°C while 3.4 mm for 10°C determined on the base of TS measurements. This is due to the big sensitivity of the construction deformations of local and global character to the changes in the temperature. The observations during monitoring were confirmed by the numerical analyses of the construction deformations resulting from the changes in the temperature (Olaszek et al. 2017).

The resulting discrepancies will be the subject of further comparative analyzes for both methods. In particular, research is conducted on a better refraction model for TS observations taking into account the specificity of bridge measurements.

IV. CONCLUSIONS

This article presents a bridge structure monitoring system whose main elements are inertial transducers used to determine vertical displacements using an indirect method. The elaboration of the data from inclinometers together with an accelerometer for indirect displacement measurement under the dynamic load is the main achievement of the system.

The so far tests of the system proved its usefulness for monitoring bridges in high speed railway as well as its possibility to achieve high accuracy while determining dynamic displacements using an indirect method.

Studies have confirmed the need for periodic measurements of total station for calibration and verification of static readings from inclinometers. Should also be considered using other measurement methods, for example time synchronized, periodic photogrammetric measurements could be also useful to verify static displacements determined from dynamic measurements.

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