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Diagnostic surveys of displacements of a rotating pedestrian bridge during its movement

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ABSTRACT

Innovative engineering structures are exposed to disturbances in their operation, especially under the influence of unexpected external factors. Sometimes this can lead to damage or cause threats to users. An example of such a construction is a rotating footbridge at the mouth of the Słupia River to the Baltic Sea, which under conditions of significant swelter began to fall into undesirable vibrations and crackles during rotation. The footbridge is suspended with steel cables to the swivel located on top of the supporting structure. In order to assess the phenomenon, a series of control measurements of selected elements of the footbridge were made during its opening and closing procedure. Among them, the most relevant information was obtained from TS measurement, inclinometry and photogrammetric image analysis. The use of biaxial inclinometers directly on the footbridge allowed identifying its lateral tilts during rotation. The size and the nature of the footbridge vibration were determined by photographic recording displacements of two pairs of LED lights using a fast digital camera located on the platform in its axis of rotation. The article presents technical problem and related aspects, discusses the course of research, presents the results obtained and formulate main conclusions. Resolving all these aspects illustrate how a surveyor choosing different available measurement techniques can carry out measurements in order to detect an incomprehensible phenomenon.

I. Introduction

A. *Subject and purpose of research*

Some building structures require periodic inspection of their technical condition, mainly in terms of ensuring ultimate states of load and serviceability. The reasons for the threat of deterioration of the strength properties of a building object can be discerned from the side of external factors – operational load, geophysical, hydrological or weather factors. Sometimes the causes lie in the technical solution of the object (design of static forces and stresses) or in its dynamics. Dynamic problems were identified in the case of a pedestrian footbridge, which is a crossing through the estuary of the Słupia River to the Baltic Sea (Fig. 1). The footbridge is suspended on five pairs of steel cables to the rotary head at the top of the pylon on one side of the channel and also at the same site it occupies a resting position. In order to allow the passage of people to the other side, it is being rotated by almost 90°. For this purpose the 50-meter footbridge is embedded on a rotary mechanism controlled by two complementarily operating engines.

It was noticed, that under extreme atmospheric conditions – direct sunlight and air temperature over 25° C – the rotating part began to fall into undesirable vibrations during its opening and closing. It was feared that this could lead to a loss of load capacity and even to damage the rotating mechanism.

Figure 1. View of the footbridge and TS Leica TCRP 1201+ in the harbour scenery

The 50-ton footbridge is suspended to sliding bearing located on top of a 30 meter hight two-legged pylon. Because the platform loads the pylon on one side, the load is balanced by two steel cables anchored in the ground on the opposite side of the pylon (Fig. 1). In the open position (Fig. 2b), the loads act on the footbridge symmetrically, while during rotation the loads are bent in one direction, which particularly affects one of the cables. While working on the construction of the port adjacent to the footbridge, the stability of the anchorages could have been disturbed, therefore the thesis on the influence of this factor as a source of undesirable vibrations was adopted.

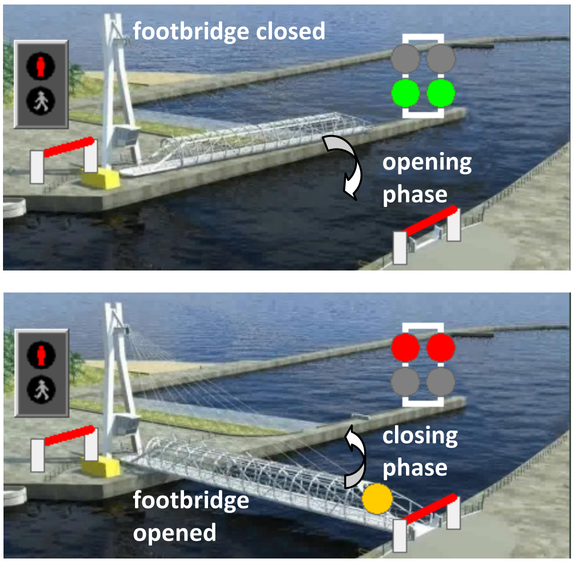

Figure 2. Two extreme positions of the footbridge:
a) resting or closing, b) opening [source: control panel of steering module]

B. *Measuring possibilities considered*

The task of measuring spatial displacements of selected points on the object was entrusted to the surveyor. Based on the identified type of the phenomenon, he chose a trigonometric method for this purpose. In modern total stations (TS) recurrent trigonometric measurements to targets on the object can be performed automatically. Using prisms as targets, the measurement can be currently performed at a frequency of several Hz, completely without human intervention. Among others such opportunities are provided by total stations of Leica Viva series (Lienhart et al., 2016; Marendić et al., 2016; Psimoulis and Stiros 2008, 2013). In automatic total stations high-speed measurements have been provided thanks to the features such as automatic target recognition (ATR) or continuous following its movement (PowerSearch). The continuous Tracking or SynchroTrack mode are also useful. Tests made by Kirschner and Stempfhuber (2008) are a guarantee of obtaining correct results using the mentioned functionalities. An essential condition is the visibility of the prism from the stable position of the instrument. In the case of the tested bridge, this approach was used to measure points on fixed construction elements.

With regard to moving parts, especially when the investigated phenomenon is carried out with high frequency, it is necessary to use other measurement methods. Among the cited solutions, photogrammetric measurements or the one based on the use of non-geodetic sensors are commonly mentioned. To better understand the phenomena occurring on the rotating part of the tested footbridge, long-term inclinometer measurements were selected. The literature has noted numerous effective attempts to use inclinometers (Hou X. et al., 2005; Hou Sh et al., 2018; Yoga and Hoit, 2016, Yu et al. 2013), also in multisensor systems (Akpinar and Gulal, 2012, Olaszek et al. 2018). The inclinometer based technique was also tested and implemented by Wyczalek et al. (2013a, 2013b).

The photogrammetric method also found many applications in bridge monitoring (Jiang and Jauregui, 2010, Lacis, 2016, Özgür et al., 2014, Park et al., 2015) and other constructions (Scaioni et al., 2014). Due to the possible high registration speed, both of the above methods provide the possibility of dynamic survey without human intervention (Marques et al., 2016; Wyczałek et al. 2013b). Inclinometric methods directly record the tilts, while in relation to photogrammetry IT solutions, ie. DIC techniques (Piniotis et al., 2016; Xu and Brownjohn, 2017) are available based on tracking changes in the position of initially defined pattern in photos. One of the possible solutions is to mark the measuring points using luminous targets (Özgür et al., 2014). The conclusions from the bibliographic review confirmed the authors of this work in the belief that the best results will be obtained by registering several LED lights on the site. For the location of images of lamps, the technique of adjusting the maximum brightness in the pictures was used for (Gruen, 2012).

II. MEASUREMENTS CARRIED OUT ON THE TESTED OBJECT

A. *Trigonometric survey*

Trigonometric method was used to determine, at intervals of several days, the range of displacements of selected supporting elements of the footbridge (pylon, lashings, nodes) during its rotation. As a result, it was expected to obtain a set of values of parameters describing the shift of these elements and its changes in the function of time.

Automatic measurement from the ground station of Leica TCRP 1201+ robotic total station was made to prisms arranged on the monitored elements, as well as to the group of reference points. In order to measure dynamic phenomena, cyclical tacheometric survey was taken to a selected prism in the automatic mode with a frequency of 5 Hz and in the target tracking mode. From among the places selected for tracing, the most interesting results were provided by the point (prism) placed under the rotational suspension head of the footbridge (Fig. 3).

Figure 3. Leica GPR112 prism in the lower part of the rotating head holding the footbridge with the help of cables.

Due to the fast measurement from one station, in one series, the observations did not require performing calculations other than routine transformation of the observed polar quantities to the orthogonal coordinate system related to the shape of the footbridge.

Significant results of tacheometric survey in terms of evaluation of horizontal displacements of the head are illustrated in Figure 4 which show the behavior of the rotating head in the full cycle of the rotation of the platform (on the left) and in the first phase of opening (on the right, marked on the left graphs by the green square). The horizontal lines correspond to the stationary position of the platform, while curves – to the changes in position of the head during its rotation in opening and closing phase. Vertical lines show the moment of locking/unlocking the rotating platform.

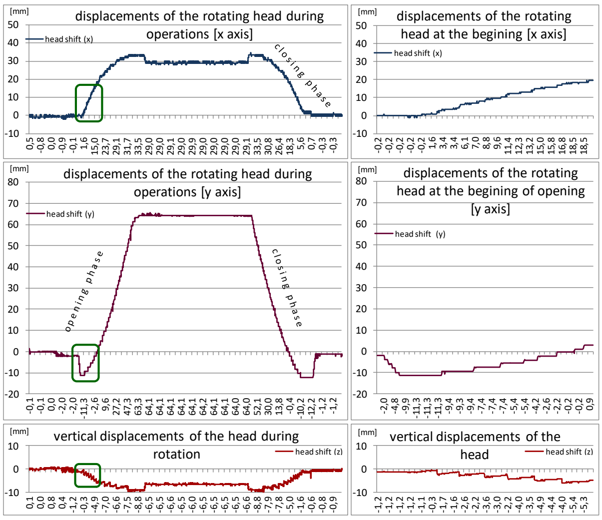

Figure 4. The graph of displacements of the rotating head

Direction 'x' in Figure 4 is oriented along the channel, 'y' axis – at perpendicular direction, corresponding to the orientation of the footbridge after its opening. Scale descriptions illustrate shift of the mirror in directions of individual axes. They have reached 32 mm along the x axis, 64 mm in the y axis and 9 mm in the vertical direction (z axis). Similar quantities were repeated in numerous measurements what indicate the stability of the suspension structure of the bridge. The step changes in the diagrams result from the nature and precision of distance measurement in the tracking mode (±1 mm). This study did not show the moment when the footbridge oscillates, and thus it was found that unexpected displacements are not transfered to the head. Some minor up- and downcasts in the diagrams are the result of temporary trembling resulting from other factors (wind, people passing).

B. *Inclinometer measurement*

Sources of undesired phenomena should therefore have been sought on the platform itself, but the measurement of these places with the total station was a bigger technical problem, because the change of the footbridge position caused changes in the visibility of the prisms (as shown in Figure 5), including loss of visibility due to obstructions by some elements of the structure. An important factor was also capturing the moment of start and course of vibrations of the footbridge, which were noted earlier for turning it of 5-10° from the open position.

In order to evaluate changes in the slope of the footbridge, two two-axial inclinometers Posital Canopen AGS15 were installed on it. Inclination measurements were recorded continuously for several days (Figure 5).

Figure 5. Inclinometer Posital AGS15 with counting device and the prism mounted at the end of the footbridge.

The values of measured inclinations were prepared in graphical form as presented in Figure 6.

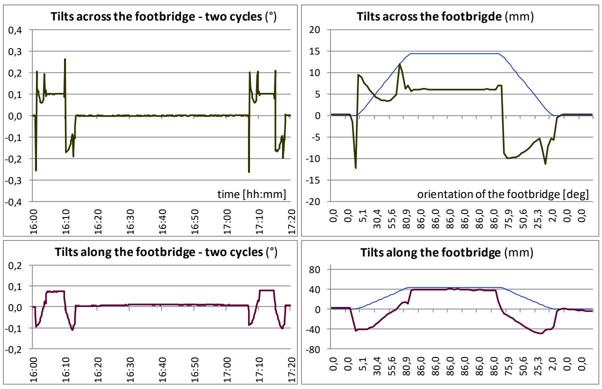

Figure 6. The graphs of two-axial inclinations of the footbridge during its opening and closing

The diagrams on the left show the characteristics of inclinations: across (at the top of the graph) and along the footbridge (at the bottom). The time interval includes two successive turns of the footbridge and the rest time. Repetitive scheme of inclinations can be noticed, similar to such diagrams obtained from other numerous measurements. The diagrams on the right are an enlarged illustration of inclinations in single cycle (the turn of the platform is marked by blue line and described in the scale along the horizontal axis). The change of inclination across the footbridge from $+0.2°$ to $-0.2°$ (± 12 mm) occurring at the beginning of opening and closing corresponds to the moment of vibration of the structure. The results of inclination measurements served as an inspiration to make more detailed photogrammetric measurements.

C. *Photogrammetric measurement*

For the need of photogrammetric elaboration, Point Grey BFS-U3-51S5M-C camera with a CMOS matrix 2448×2048 at 75 FPS and a Sony IMX250 80 mm lens have been used. The camera was installed on a gimbals placed in the axis of rotation of the footbridge. Due to the expected nature of the phenomenon, the speed of registration for the full range of 75 FPS was determined.

Measured points were marked with LED spotlights, whose changing position in the images of successive phases of footbridge movement was identified using the typical image correlation method, SWIFT. Five diodes were registered, two on each side of the rotating platform at the place where the fifth (lamps 1 and 2 in the Figure 7) and third (lamps 3 and 4) pair of steel cables are attached, and an additional lamp at one of the points to assess the discrepancy of results.

As a result, a set of coordinates was obtained in a plane perpendicular to the axis of the photograph, consistent with the axis of the footbridge. Thanks to the suspension of the camera independent of the photographed object, the desired effect in the form of graphs of changes was obtained. One of the obtained graphs is shown in Figure 7.

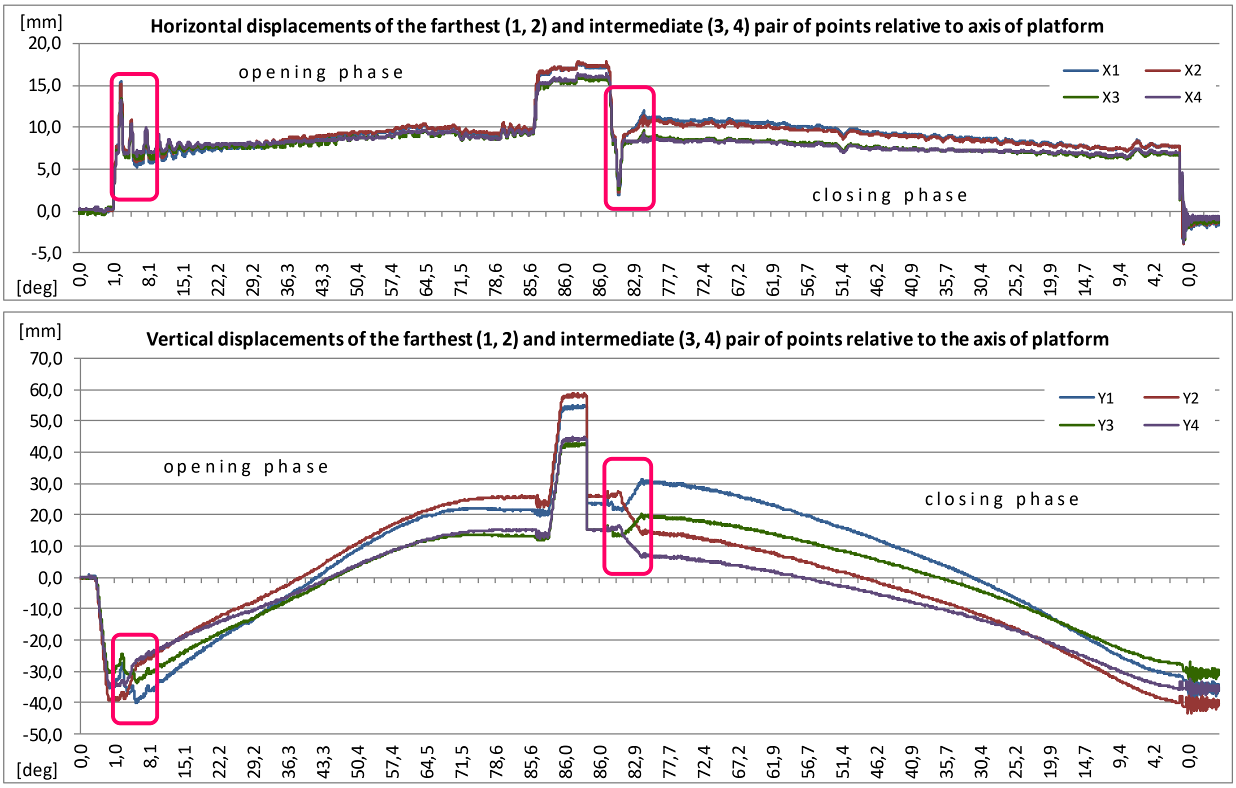

Figure 7. The graphs of horizontal and vertical vibrations recorded by high-speed camera

The four color lines shown in graphs refer to the four recorded LED lamps. The trace of two further lamps is represented as the upper pair of lines, and the closer - the lower pair.

In the upper graph are seeing picks at the beginning of the two phases of rotations and suppressed wave – in opening phase. They correspond to the moment of occurrence of cracks in the structure.

The graphs confirm the occurrence of unfavorable phenomena at the beginning of the opening and closing process of the footbridge. In the first phase (left pink rectangles) cyclic, disappearing horizontal vibrations were recorded. In the closing phase, after initial launch of rotating the platform, it was tilted in the opposite direction (the second pair of pink rectangles) what was identified as a source of unexpected vibrations and knocking.

III. Summary

The purpose of the work was to detect the cause of the occurrence of an unexpected phenomenon, which in the holiday village does not positively affect the feelings of tourists. On the practical point of view it was to propose an action that would eliminate the risk of incorrect footbridge work. The presented sequence of surveying works arose successively as a result of inference based on the results of previously performed measurements. Therefore, the results of individual actions should be treated as the successive steps in the process of searching for the causes of this phenomenon.

Based on the conclusions reached, the decision was made to replace the swivel head with a ball bearing. As a result of the repair work, the desired effect was obtained and now the footbridge is working correctly. According to the authors, the elaboration of specific applications was possible only thanks to curiosity in performing various measurements by a geodetic team.

The aim of the paper was to show how a surveyor in his work can use various available surveying techniques – classic ones and those that go beyond the standard of the profession – to register and describe the spatial phenomena occurring on engineering objects. Each of the described techniques has brought significant knowledge about the behavior of individual elements of the tested structure. Their complementary character has been shown, leading to effective engineering inference. This testifies to the need for a flexible approach to solved problems in the field of structural health diagnostics, based on knowledge and professional experience.

The use of various approaches and the geodetic interpretation of their results allowed for the correct assessment of the studied phenomenon. The results of the measurements, summarized in the tables and shown in the diagrams, were used to perform appropriate expertise in the field of structural mechanics. The results were used to design and perform correction of the suspension mechanism what resulted in the elimination of undesirable behavior of the footbridge.

The described work was not aimed at making a significant contribution to the development of the theory of measurement methods, but their application based on the available knowledge in the field of measuring and processing of the data obtained. As a result, theoretical knowledge gains a new meaning, so valuable from the point of view of further analyzes and projects leading to the protection of the efficient handling of objects exposed to operational damage.

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