Innovative methods of measuring bridge displacements under static and dynamic loads

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1. Introduction

Theoretical and experimental analysis of the displacements of bridge structures under static and dynamic load is important in long-term monitoring systems (SHM - structural health monitoring) or in short-term measurements (bridge load testing). The bridge displacement response is primarily sensitive to the stiffness of the bridge, whereas the acceleration response is affected by many other parameters so the bridge dynamic displacement is more suited than acceleration for updating the railway bridge stiffness [4]. Accurate measurements of deflections are also important in the validation of road bridge models [12].

The measurements of displacements in an automatic, unattended mode nearly always create considerable difficulties. Major difficulties are encountered especially in case of structures with restricted or impossible access to the area under them (bridges over busy roads, railway lines or rivers). In case of such located spans and additionally of great length problems appear both during static and dynamic measurements. Due to the specific nature of short-term bridge tests and long-term bridge monitoring, specially designed innovative systems are frequently used for displacement measuring. Making a reference to stable external or internal reference points is an important element of systems created for displacement measurement.

2. Computer vision method – external reference points

A special method for the investigation of the dynamic characteristic of bridges has been developed. It is based on the photogrammetric principle; however, the viewing system is equipped with an additional reference system, which decreases the sensitivity to vibrations and an analysis system which enables image analysis. The method is used for monitoring and real-time measurement of the displacement of chosen points at bridge structures [10]. The method presented is based on observation of bridge structure particular point using the CCD camera with telephoto-lens. The pattern, black cross on white background, is placed at the analyzed point and imaged by the optical system at the CCD matrix. Two alternative opto-mechanical systems are proposed: one- and two-channel system.

The first system (one-channel system) allows to observe one bridge point by a single camera. The camera is equipped with one telephoto lens of 1000 mm focal length. Many bridge tests have been carried out using this vision system and it has been observed that the reference system is one of the most important elements which dictates the measurement accuracy. The reference system has to provide the accurate displacement determination. There are two possibilities of reference system:

location of a single point (point of camera position); location of two points - adding immovable points of tested structure which can be observed by the camera.

The second solution assumes additional monitoring of the reference (immovable) point which is usually situated at the nearest bridge support (Fig. 1). It requires introducing two-channel optical system which enables simultaneous imaging of measuring and reference points at the CCD matrix.

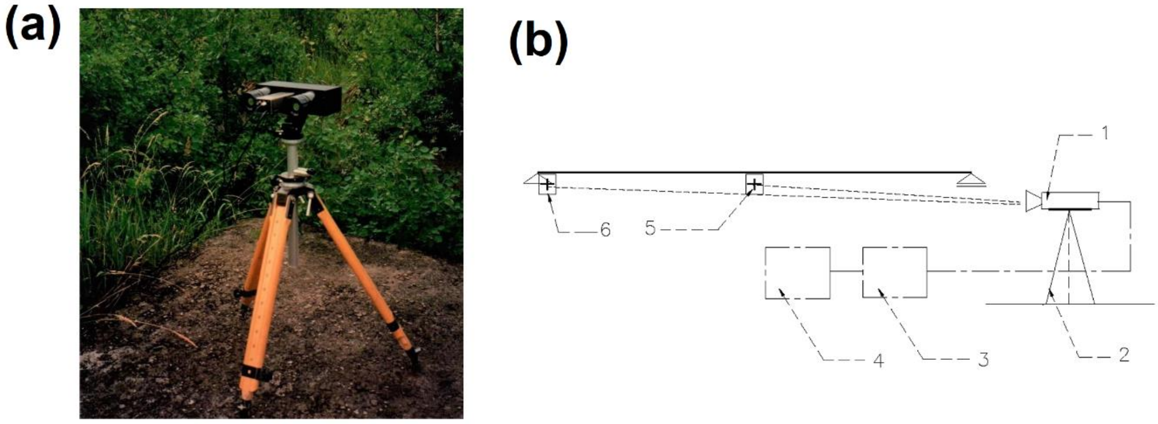

Figure 1. Additional reference point system; (a) photo of camera with two telephoto-lenses and stand; (b) vision system schema: 1 - camera and two telephoto-lenses, 2 - stand, 3 - computer and image digitizer, 4 - monitor, 5 - measuring pattern, 6 - reference pattern

One of the first tests was performed at the new highway bridge. During the dynamic test the deflections in midpoints (33 m span length) were measured. In the case of over-ground span the deflection was also measured by inductive sensors to test the vision method. The results of mechanical and vision methods were compared. After correction with the reference point the error of the vision method was equal to 0.1 mm (0.4 pixel). The maximum error without correction was equal to 1.6 mm (7.0 pixels).

The method was elaborated and presented above 20 years ago. It is still cited in many publications today with emphasis on the innovative method of vision-based dynamic measurement in two directions [1,5,6].

3. Static deflection monitoring system making use of inclinometers - internal reference points

Continuous multipoint deflection measurements (with sampling frequency of at least several times per minute) are difficult or practically impossible to be made in case of bridges with no possibility of equipment assembly under the examined spans). It is important to apply such measurement methods which give the possibility to measure bridge deflections without the necessity of using external reference points. Identification of this need has led to the development of a new measurement system, the main elements of which are inclinometers. The application of inclinometers to automatic monitoring of bridge structures under static and dynamic loading has often been presented in literature [2,3,7,9].

The new elaborated deflection monitoring system makes use of a network of inclinometers. Cubic spline curves which enhance the accuracy of the results are used in the calculation of deflection lines [11]. The designed system is able to monitor bridge deflections in one or two lines along the bridge. We can use one network (up to 20 inclinometers) to monitor one line along the bridge and two networks (up to 20 inclinometers) two monitor two lines along the bridge. The designed system was tested in monitoring of bridges during static load testing (Fig. 2).

Figure 2. Monitoring of the deflection during static bridge load testing; (a) view of the bridge; (b) inclinometers location at the bridge deck.

A series of comparative tests of displacement measurements with the use of inclinometers and the reference method (total station or inductive transducers) were carried out. The tests were carried out during static test loads on objects with different spans and thus different maximum values of the measured deflections. When using a set of 6 inclinometers, the discrepancies in the results ranged from 0.3 to 2.5% compared to the value measured by the reference method; with the measured maximum displacement values from 175.0 to 3.5 mm. All testing employ reading frequency of not less than 3 times per minute.

4. Dynamic deflection monitoring system making use of inclinometers and accelerometer - internal reference points

One of the most important elements of the developed solution is its innovative system of indirect measurement of displacements based on measurements using inclinometers and accelerometers. Many researchers 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 [8,16,17].

Whereas the method presented here is based on the integration of the signals from inclinometers and accelerometers. Inclinometers are installed in one line on a 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 [13,14]. A similar way of integrating the signals from an inclinometer and an accelerometer, used to determine lateral displacements of a railway bridge support is presented in [15].

The system presented herein was checked during one-year monitoring of the arch bridge located in high speed railway (Fig. 3).

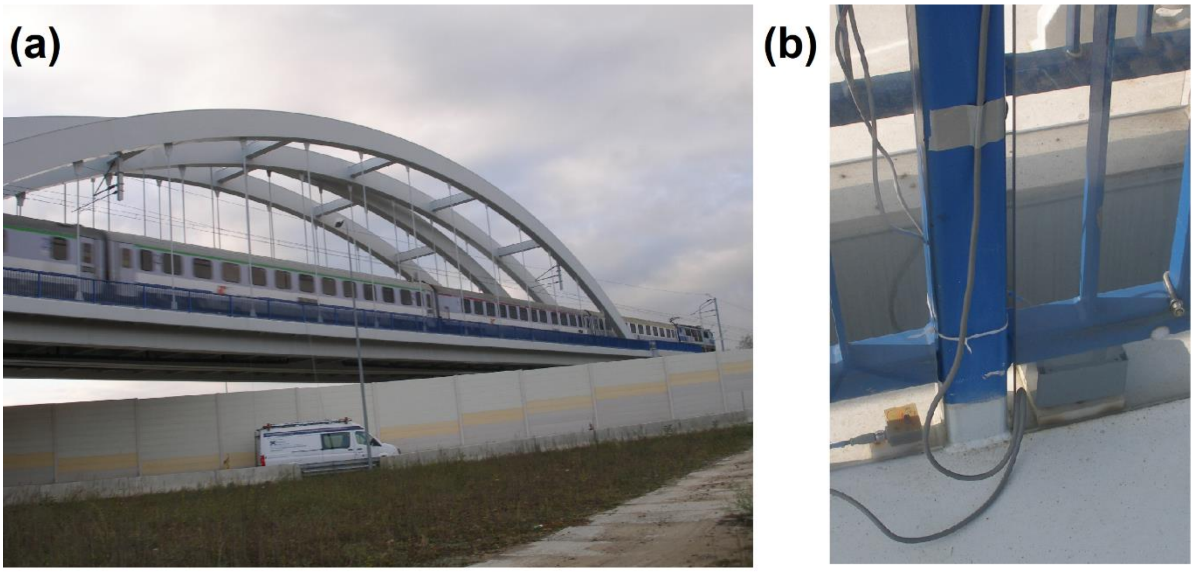

Figure 3. Monitoring of the dynamic deflection under service load; (a) view of the bridge; (b) accelerometer and one of the three inclinometers and location at the bridge deck.

The one-year 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 displacements using an indirect method. The measurement errors determined using the indirect method in relation to a reference method did not exceed 0.84 mm (4.9%) for extreme values during separate locomotive EP09 and cars passages and did not exceed 0.54 mm (7.5%) for extreme values during Multiple-unit trains ED250 passages.

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