Inertial Sensors

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Inertial sensors are sensors which do not need any referential points. They are based on inertia. Accelerometers and inclinometers are one of the most popular used in Structural Health Monitoring (SHM).

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1. The implementations of inclinometers and accelerometers in bridge deflection measurements

Many researchers carry out work related to the use of inertial sensors to indirect measurement of dynamic displacements. 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 of correcting such errors suggested in [1][2][3][4][5], but it is generally not possible to accurately estimate the displacements on the basis of accelerations without additional measurements, such as strain gauge measurements [6][7]. In [8], another solution was presented in which accelerometers were used to define the angles of rotation in place of inclinometers, and the deflection was then determined. In [9] , the research studies of the dynamic displacement measurement system using one passive-servo electromagnetic-induction velocity sensor are presented. The results of the system tests at the shake table test show that direct reference-free displacement errors are less than 10% when compared to linear-variable-differential-transducer (LVDT) measurements.

A number of articles related to the use of inclinometers for monitoring automatic displacements of bridge structures were published. Most of those papers are limited to measurements under static load, but not all articles contain information on the accuracy achieved. The paper [10] presents a static test of a post-tensioned concrete highway bridge (main span is 150 m), and the deflection was about 40 mm with an error of less than 5%. In [11] [12], the method was applied on two bridge spans (length of 24 and 30 m), and the maximum deviation for a deflection of about 16.0 mm reached 1.2–1.6 mm. The article [13] presents tests with the use of high-precision inclination sensors and results concerning two structures of extreme spans (160 versus 18 m) and maximum measured deflection values (175 versus 4 mm). The deviation between the inclinometer system and the reference measurements was 1.25 versus 0.12 mm (0.7% versus 3.0%). Paper [14] presents the use of inclinometers to determine deflections at a bridge with a 64 m span length during static and dynamic load tests. During the static test, deflections were about 22 mm and relative errors were within 2%.

Article [15] presents the use of inclinometers for tests of a railway steel arch bridge (100 m span length); the train's maximum speed equaled 120 km/h, with deflections of about 3.5–3.8 mm, and the deviations to the reference methods ranged from 2.9% to 4.5%.Works using inclinometers to determine displacements under dynamic load and high-speed train passages are presented in [16]. The inclinometers were installed at a 30 m span length, the speed of the train was about 200 km/h, and the deviations to the reference methods ranged from 3.0% to 8.3%. In addition, article [17] presents discussion comments to the method presented.

The new method presented here is based on the integration of the signals from inclinometers and accelerometers. Solutions using measurements of inclination and acceleration are also presented in the literature. In [18], the main sensor is the accelerometer that is used to evaluate both inclination and three-dimensional acceleration, both dynamic and static. The system may be successfully adopted to detect rockfall events on protection barriers, as well as to monitor landslides or the integrity of structures like bridges and buildings. A way of integrating the signals from an inclinometer and an accelerometer in order to determine lateral displacements of a railway bridge support is presented in [19]. The results of the simulation test of a cantilever beam indicate that the displacement could be accurately estimated even in the events where pseudo-static displacements due to non-symmetrical heavy train loading are dominant.

2. The integration the signals from inclinometers and accelerometer

Based on the analysis of existing technologies, the main problems of the work have been defined. In the case of dynamic displacement monitoring, the main problem was considered to be the development of a method that would have an accuracy close to the existing methods using inclinometers designed for static applications and, at the same time, have no limitations, due to the limited possibilities of dynamic measurement using inclinometers designed for dynamic applications. The system has been developed mainly to determine the dynamic displacements associated with the passage of a train over a monitored bridge. Integrated signals from inclinometers and accelerometers recorded during the train's passage are used to determine the dynamic movement.

Inclinometers are installed in one line on a bridge span and accelerometer at the point of displacement examination. Signals from inclinometers before the train enters the bridge were used to determine static displacements. During train passage, signals from the inclinometers are used to determine the so-called quasi-static component of a displacement, and the signal from the accelerometer is used to determine the dynamic component.

3. Results and Conclusions

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

Tests of the system carried out so far proved its usefulness for monitoring bridges in a high-speed railway (up to 200 km/h), as well as their possibility to achieve high accuracy while determining dynamic displacements using an indirect method. It should be noted that this accuracy is close to or better than those of other measurement methods designed for continuous monitoring and not requiring reference points. It has been confirmed in long-term tests on a railway bridge in operation. This was the primary purpose of the presented tests.

The proposed system of optimization of the signal processing parameters requires comparative measurements at the beginning. These measurements must be carried out at all deflection monitoring points. The displacement courses obtained after its application are characterized by the relatively high accuracy of the extreme values determined, such as reconstruction of the shape of the forced vibration course during train passage like free vibration after train exit from a bridge.

It seems to be advisable to carry out further works connected with finding the reasons for much bigger measurement deviations in the case of some train passages. It seems advisable to develop an algorithm with the auto-modification of signal processing parameters on the basis of analysis of recorded signals from inclinometers and the accelerometer, e.g., based on their spectral analysis. Developing a method of algorithm parameters auto-modification could lead to a reduction in the number of measurements with much larger deviations than the others. Thanks to such an auto-modification of the algorithm, it might also have been unnecessary to make comparative measurements at many points of the structure, in the phase of launching a monitoring system at a new structure.

The presented monitoring system was installed and tested on the single-line railway bridge; thus, the loading generated by passing trains induced mainly the bending mode of the structure. An application of the monitoring system to multi-line railway structures seems to also be possible; however, additional transducers may be required to identify and quantify the influence of twisting modes for vertical displacement assessment of the structure.

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