WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.143057
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 4 2022

pp. 607 –616

Research paper

Laser-inclinometric method for displacement measurements in structural health monitoring

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Abstract: The paper presents a method of structural monitoring using measurement of vertical displacements realized optically by horizontally directed laser beam. A measuring device with an integrated rangefinder and inclinometer sensor was developed. Inclinometer sensor are used to correct measurement results of the rangefinder in order to eliminate errors resulting from spatial position changes of the laser beam. Such a solution was adopted as an alternative to a more complex and demanding method, which is the stabilization of the laser beam orientation. The proposed inclinometric correction method allows in a simple and clear way to eliminate a serious problem of the displacement measurement method with a perpendicularly directed laser beam, which is inevitable in practice the lack of permanent stability of the measuring device position. The developed measuring device is wireless, both in terms of power supply and communication with other elements of the monitoring system. In order to verify the correctness of measurements carried out by the developed device, on site tests were carried out in two industrial-warehouse buildings with functioning monitoring systems using other measurement methods, earlier verified. The tests confirmed compliance with the indications of the existing system at a level completely sufficient for structural monitoring system purposes. The conducted research show that the proposed method of displacements measurement with inclinometric correction of errors, provides accurate and reliable results, allowing also to obtain additional information about the behaviour of the structure in the place of installation of the measuring device.

Keywords: inclinometer, laser-inclinometric measurement method, monitoring of deflections and rotations, structural health monitoring, wireless structural monitoring

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1. Introduction

Ensuring an adequate level of safety of the structure is a basic criterion that must be met by the building facility at every stage of the investment, from the design phase to the operation. The greatest attention is obviously required during the operation period, when the object is exposed to changing conditions and actions, which in combination with hidden design or execution defects can lead to failure or even collapse. Particularly at risk here are large objects with lightweight structure, such as those used in warehouses, commercial and industrial buildings. Apart from obvious design or execution errors, the direct causes of failures and collapses are usually climatic actions such as excessive snow and ice loads, excessive wind loads or intensive rainfall. The influence of climatic actions on buildings has been described in various works, such as Geis et al. [1] and Giżejowski et al. [2]. The carried out analysis confirm that the majority of collapses occurred in buildings with lightweight roof structures [1,3], characterized by a significant share of variable loads in the total actions, and thus high sensitivity to above-normal climatic actions. If, in this context, the progressing tendency to use increasingly lighter construction solutions is superimposed on the intensifying extreme weather phenomena, such as intensive snowfalls, heavy rains or hurricane winds, the overloading of the structure and thus a threat to its safety becomes real.

One of the tools supporting the process of counteracting structure overloading is structural health monitoring. Depending on the type of structure and the requirements and limitations of the monitoring system, most often displacements, strains, dynamic characteristics, temperature or weather phenomena are monitored, and in some cases vision methods are also used [2–11]. In practical applications, monitoring systems are most often based on displacement measurements [2–10]. These are quantities characteristic for the behaviour of most structures, simple in measurements and usually not generating interpretation problems.

The paper presents the application of a method of displacement measurement realized by laser devices with laser beam directed perpendicularly to the displacement direction. In order to eliminate errors resulting from changes in spatial position of the laser beam, a correction of results based on measurements of angles of beam rotation with integrated inclinometer sensors was applied. In the beginning the conditions for the use of typical displacement measurement methods were discussed, with particular emphasis on the method of measurement of the laser beam directed perpendicularly to the direction of measured displacement. Then the concept of measuring device with integrated rangefinder and inclinometer sensor is presented. The next stage is to discuss the testing of the developed device in operating industrial-warehouse buildings and to formulate conclusions from the work carried out.

2. Methods of monitoring structure deflections and conditions of their application

Functioning structural monitoring systems most often use linear displacement measurements, which directly reflect the behaviour of the structural element/structure. In displacement-based structural monitoring systems, the following devices/methods are most commonly used: laser rangefinders [2, 3], total stations [7], hydrostatic levels [4, 7], GPS techniques [7], inclinometers [6–8] and sometimes vision-based methods [5, 10]. Each of these devices/methods has certain advantages but also limitations, hence the possibility and validity of their application is determined by specific conditions, including costs and complexity of the devices. The most widely used are laser rangefinders, which, being inexpensive and simple devices, are suitable for solutions dedicated to typical objects and structures. However, the classic application of laser rangefinder for direct measurement of vertical deflection of roof structure is characterized by certain limitations, which make it difficult to use such a method. In typical applications inside buildings, i.e. where monitoring systems are most often used, the problematic factor is the limitation of the freedom of use of the object related to the necessity of making measurements of the distance of the monitored point of the structure from a fixed place of the building. Such a place is usually the floor, which on the one hand constitutes the usable area of the building, and on the other hand locally should serve as a "measuring target" and cannot be covered. The elimination of this problem was served by developing such a method of measuring displacements of the structure, which, based on laser rangefinders, would not hinder the use of the building floor. Such method is the measurement of vertical displacements of roof structures by horizontally directed laser beam (Fig. 1), developed on the basis of [12]. In this method, the measuring device cooperates with a measuring target to which distance measurements are made and both are attached to the structure in the roof zone. This means that the behaviour of the elements of the structure during their normal operation affects the behaviour (orientation) of the monitoring system devices attached to them, and consequently also the results of the measurements. Therefore, a number of analyses were carried out to recognize this issue and to solve possible problems.

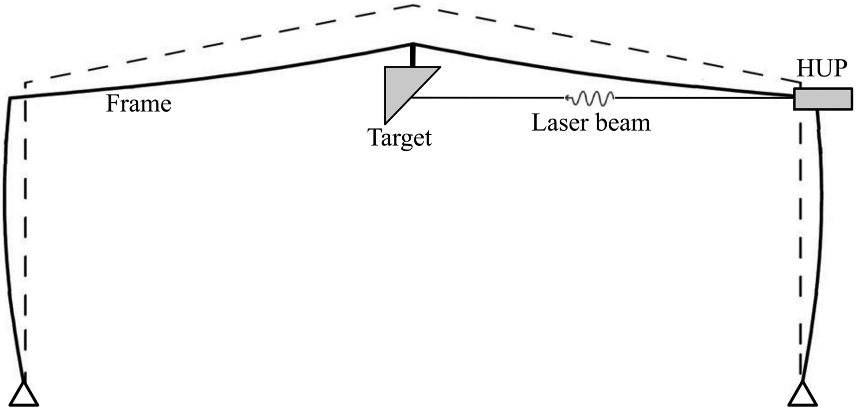


Fig. 1. Scheme of deflection measurement with a horizontally directed laser beam

The issue that is most important from the point of view of the correctness of monitoring system indications is to take into account the impact on the measurement results of the laser beam deviation from its initial position. Even small deviations, at measuring distances of several meters can lead to errors comparable to the measured values of deflections. Analysis of different structural systems shows that in case of typical installation of measuring device on the column of the structure, the biggest errors resulting from the laser beam deviation will occur in the frame systems and they will often exceed the ranges of monitored deflections. In the case of traditional column and beam systems, these errors are smaller, but can also reach up to 50% of the measured displacements. The solution to this problem can be e.g. installation of measuring device on independent from the structure, stable load-bearing system not exposed to the external influence, but it brings additional costs and inconvenience in functioning of the object. Another solution is to stabilize the position of the laser beam, which is possible, but with the required high accuracy of this position, it can be expensive. An alternative to stabilizing the laser beam is to correct the results of measurements taken with a rangefinder, based on measurement of the rotation angle of the laser beam. With sufficiently high measurement accuracy of this rotation angle, it is possible to reduce the deflection measurement error resulting from the laser beam deviation to fractions of a millimetre.

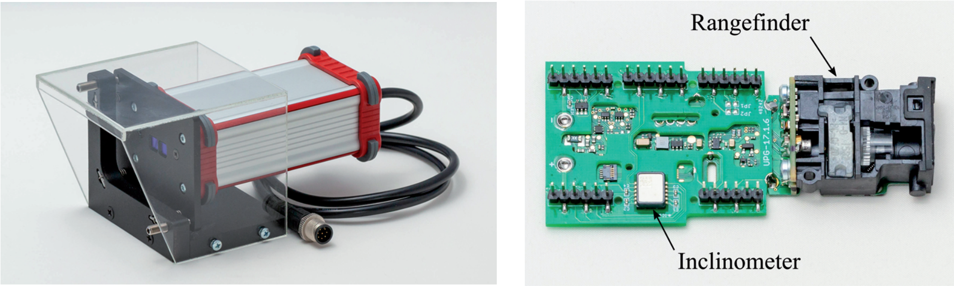
An issue that is often not negligible in terms of influence on deflection measurement results is the change of the base distance of the measuring device from the measuring target. The biggest values of this change occur in frame structures with significant roof slope inclination and may be of the order of several dozen mm, reaching even 50% of the measured deflection range. In structures with truss roofs and multi-bay roofs, the changes are much smaller, but they can still be of the order of several percent of the measured deflection range. The analysis shows that in some cases, the changes in the baseline laser beam length are so significant that they must be accounted for in the monitoring system. In this case, it is necessary to adjust the measurement method accordingly, e.g. directing the laser beam along the slope instead of the standard horizontal position. This generally limits the measurement error resulting from a change in the baseline laser beam length to a negligible or at least acceptable value, i.e. less than 5% of the range of measured deflections.

Another issue that needs to be analysed in terms of influence on deflection measurement accuracy is rotation of the measuring target due to deformation of the structure. While in case of distancing the target from the structure, e.g. due to dimensions of structural elements, this influence can be significant, with standard solutions the deviations will not exceed 1 mm. Therefore, to avoid excessive errors here, the measuring target should be attached to the structure without spacing and as close as possible to the axis of the component being monitored.

In the case of deflection measurements, the issue of roof uplift due to wind suction must also be resolved, regardless of the measurement method used. In some systems, the displacement of the roof structure due to wind suction may even significantly exceed 50% of the measured deflection range, changing the results in the direction that reduces safety. However, given the ease of interpretation of wind suction related measurement disturbances and the short duration of wind gusts, the simplest solution to eliminate erroneous results is for the system to automatically skip them and replace them with repeated measurements.

3. The concept of a hybrid measuring device

Taking into account the above described conditions, a method of measuring vertical displacements of roof structures by horizontally directed laser beam with correction enabling elimination of errors resulting from deviations of this beam from the initial axis was developed [13]. The designed wireless Hybrid Measuring Device (HUP) (Fig. 2, Table 1) is based on displacement measurements performed with a laser rangefinder, but with simultaneous use of rotation angle measurements performed with an integrated MEMS inclinometer to correct the laser measurements.



(a) (b)

Fig. 2. Hybrid Measuring Device (HUP): (a) view, (b) electronics

Table 1. Basic parameters of the measuring device

Parameter / feature	Value	Remarks
Power	Batteries LR20 1.5 V, 2 pcs.	Working time without battery replacement 5 years
Laser diode	Class 2, Power < 1 mW wavelength 635 nm	Visible red light
Distance measurement resolution	1 mm	–
Measurement range	25–40 m	–
Working temperature range	−10 ÷ +50°C −25 ÷ +70°C	Full functionality Limited functionality
Measurement period of the laser rangefinder	5 minutes – 5 hours	Average ≥ 15 minutes
Resolution of measuring the angle of inclination of the laser beam	±0.0001°	–
The uncertainty of measuring the angle of inclination of the laser beam	±0.002°	In the full operating temperature range: −10 ÷ +50°C

The following measurements are performed to determine the current displacement value of the monitored point in the vertical direction:

- Initial value of the distance (b_0) to the measuring target.
- The initial value of the tilt angle (α_0) of the HUP optical axis when taking the distance measurement b_0.
- Current value of the distance (b) to the measuring target.
- The current result of the measurement of the inclination angle (α) of the HUP optical axis when taking a distance measurement b.

On the basis of these four values, assuming that the scattering face of the measuring target is inclined 45° to the horizontal, the vertical displacement is determined from the following relationship:

$$pp = b_0 \cdot (\cos \alpha_0 + \sin \alpha_0) - b \cdot (\cos \alpha + \sin \alpha) \tag{3.1}$$

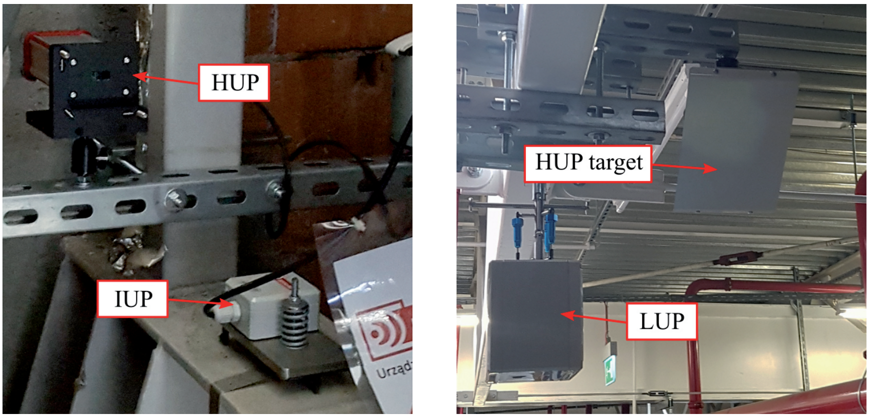
The measurement method is insensitive to the value of the angle α, both the initial (α_0) and its changes at any time. Relationship (3.1) is used in the Hybrid Measuring Device to calculate the current value of the measured vertical displacement pp of the monitored point.

The inclinometer sensors, in order to obtain the required measurement accuracy, are laboratory tested and compensation for temperature drifts of sensitivity and offset is introduced [7].

Laser measurement by means of HUP is carried out in the upper zone of the structure, usually directly under the roof elements, so it is not associated with virtually any restriction in the use of the object. As a rule, the measuring target are located in places of displacement/deflection measurements, and the measuring device (HUP) on such elements of the structure, which do not experience deflection/vertical displacement, which is usually on the columns.

4. Testing the device in functioning facilities

A test study of the designed measuring devices was carried out in two operating facilities where wireless monitoring systems using other measurement methods were installed in parallel. In one case, the existing monitoring system was based on measurements of rotation angles, while in the other case on direct measurements of deflections. Tested Hybrid Measuring Devices or measuring targets were installed in places where sensors of existing monitoring systems were placed. In the building where the existing system was based on rotation angle measurements, the tested measuring devices were installed in the vicinity of inclinometer sensors of the functioning system (Fig. 3a). The purpose of this solution was to check the correspondence or specific relation between the angles of rotation measured by the inclinometers and by the Hybrid Measuring Devices. On the other hand, in the object with installed monitoring system using direct deflection measurements realized by laser rangefinders, measuring targets associated with the tested devices were installed in the places where deflections were measured by rangefinders (Fig. 3b). The purpose of this solution was to control the convergence of deflections measured by the tested devices with the results of measurements performed by rangefinders.



(a) (b)

Fig. 3. (a) measuring device (HUP) in the vicinity of the inclinometer sensor (IUP), (b) measuring target (HUP target) in the vicinity of the rangefinder (LUP)

The test study is conducted from July 2021. The facilities where the tested devices were installed are located in the central part of Poland, in the Mazowieckie Voivodeship, where no significant snowfall was recorded last winter. Therefore, the indications of the measuring devices of the systems were also small. In both cases the results of measurements carried out by the tested measuring devices were in accordance with the results registered by the measurement sensors of the systems installed in parallel, i.e. inclinometers and distance meters. Larger values were registered in the case of the object, where the control of the indication of the tested devices was carried out by inclinometer sensors, so example results are presented from this object. The object is a hall with axial dimensions in plan 36×96 m. The monitored roof structure consists of single-span lattice girders spaced every 6 m, on which purlins and roof sheathing are based. The girders are supported on steel columns at the level of the lower chords. The shape of the girders – double trapezoidal with supporting posts – as well as the method of their supporting on the columns determined the locations where the rotation angles were measured, as well as the locations of the tested measuring devices (Fig. 3a) and targets (in the middle of the span).

Fig. 4 shows deflections graphs of the monitored girder measured directly by the tested Hybrid Measuring Device (without correction), deflections corrected after taking into account the rotation angles of the HUP, and deflections determined from measurements of the rotation angles of the girder bottom chord measured with an inclinometer sensor installed in the immediate vicinity of the tested HUP. The differences between the results obtained from the HUP without correction and the comparative results from the inclinometer sensor are significant, even close to the range of measured deflections. After correction of the measurements made with the tested measuring device, the differences oscillate close to the measurement resolution of the laser rangefinder. The very large discrepancies before correction are partly due to the intentionally chosen place of installation of the measuring device, which eliminated the problem of changing the distance of the measuring device from the measuring target, but at the same time highlighted other issues related to the installation of the measuring device in some places of the structure. In the case of the structure under consideration, much smaller deviations would occur when the device is installed to a more rigid element, i.e. the column. However, when measuring deflections realized with a horizontally directed laser beam, it will always remain crucial to correct the deviation of the laser beam from its initial position or to effectively stabilize this position.

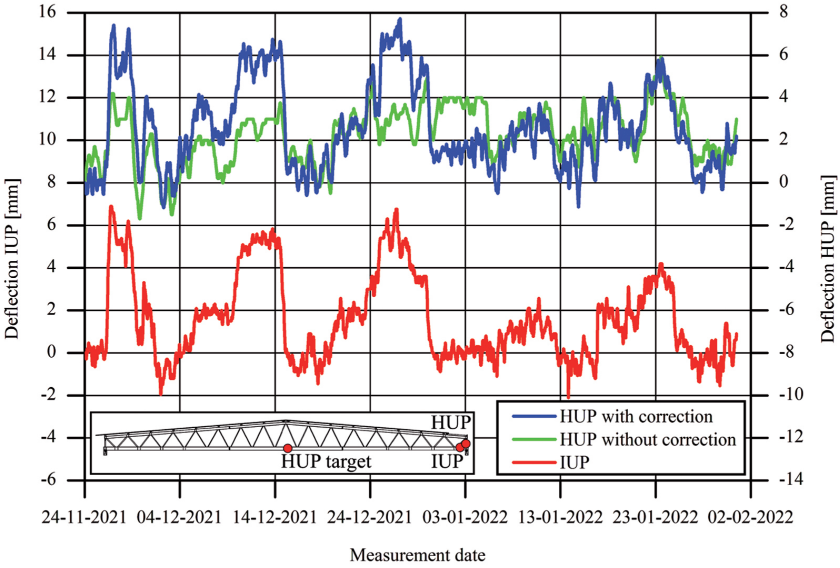


Fig. 4. Deflections measured by the Hybrid Measuring Device (HUP), before and after correction, and deflections determined by the inclinometer (IUP)

5. Conclusions

The paper presents a method of measuring vertical displacements by means of a horizontally directed laser beam, with the correction of results taking into account the change of the inclination angle of this beam. The analysis of various structural solutions in hall buildings shows that such a correction or, alternatively, stabilization of the position of the distance measurement axis is absolutely necessary. Without it, the deflection measurement results may be burdened with very big errors and become completely unreliable. Performed analyses and test studies confirm that the discussed method is a good solution, allowing for proper displacement measurement without disturbing the object's functioning. In the case of laser beam stabilization, it takes place without informing the user about its effectiveness, so in order for it to be reliable, the device, like other measuring instruments, should be periodically calibrated. From this perspective, the proposed method of correcting the measurement results, taking into account the influence of the laser beam deviation using the measurements of the integrated inclinometer sensor, is fully transparent to the user, controllable and reliable. Moreover, it allows to obtain additional information about the behaviour of the structure, in the form of the angle of its rotation in the place of installation of the device, which can be used as additional information in the analysis of the structure.

Acknowledgements

The publication uses the results of work carried out under the research and development projects No. RPMA.01.02.00 14 6207/16 and No. RPMA.01.02.00 14 b526/18 co-financed by the European Union from the European Regional Development Fund under the Regional Operational Programme for the Mazowieckie Voivodeship for 2014-2020.

References

[1] J. Geis, K. Strobel, A. Liel, "Snow-Induced Building Failures", *Journal of Performance of Constructed Facilities*, 2012, vol. 26, no. 4, pp. 377–388; DOI: 10.1061/(ASCE)CF.1943-5509.0000222.

[2] M. Giżejowski, E. Antoszkiewicz, S. Wierzbicki, Z. Pióro, "Wireless Sensor Network Systems for Structural Health Monitoring of Building Structures", in *5th International Conference on Structural Health Monitoring of Intelligence Infrastructure (SHMII-5)*. Cancun, Mexico, 2011, pp. 1–25.

[3] S. Wierzbicki, M. Giżejowski, Z. Stachura, "Structural Failures and Monitoring of Structural Health with Use of WiSeNe^{MONIT} System", in *Research and Applications in Structural Engineering, Mechanics and Computation: Proceedings and Monographs in Engineering, Water and Earth Sciences*. CRC PRESS/BALKEMA, 2013, pp. 2365–2370.

[4] M. Giżejowski, K. Wilde, J. Uziak, S. Wierzbicki, "On a Necessity of Monitoring Systems for Sustainable Development of Mechanical and Civil Engineering Infrastructure", *Botswana Journal of Technology,* 2011, vol. 19, pp. 9–20.

[5] J.C. Moore, S.S. Mahini, R. Glencross-Grant, R. Patterson, "Recording Timber Bridge Girder Deflections Using a Laser Reference Source and a High Speed Camera", in *5th International Conference on Structural Health Monitoring of Intelligence Infrastructure (SHMII-5)*. Cancun, Mexico, 2011, p. 59.

[6] H.B. Xiong, J.X. Cao, F.L. Zhang, "Inclinometer-based method to monitor displacement of high-rise buildings", *Structural Monitoring and Maintenance*, 2018, vol. 5, no. 1, pp. 111–127; DOI: 10.12989/smm.2018.5.1.111.

[7] S. Wierzbicki, Z. Pióro, M. Osiniak, E. Antoszkiewicz, "Inclinometer Method of Displacement Measurements as an Alternative to Optical Measurements in Structural Health Monitoring - Laboratory Tests", *Archives of Civil Engineering*, 2020, vol. 66, no. 2, pp. 147–164; DOI: 10.24425/ace.2020.131802.

[8] S. Wierzbicki, Z. Pióro, M. Osiniak, E. Antoszkiewicz, "Inclinometer Method of Displacement Measurements as an Alternative to Optical Measurements in Structural Health Monitoring – On Site Tests", *Archives of Civil Engineering*, 2020, vol. 66, no. 3, pp. 109–124; DOI: 10.24425/ace.2020.134387.

[9] S. Guan, A.J. Rice, C. Li, Y. Li, G. Wang, "Structural Displacement Measurements Using DC Coupled Radar with Active Transponder", *Structural Control Health Monitoring,* 2017, vol. 24, art. ID 1909; DOI: 10.1002/stc.1909.

[10] C.H.H. Carpizo, D.M. Vila, "Implementation of Camcorders to Measure Displacements in Structures", in *5th International Conference on Structural Health Monitoring of Intelligence Infrastructure (SHMII-5).* Cancun, Mexico, 2011, p. 147.

[11] Q. Li, Y. He, H. Wang, K. Zhou, B. Yan, "Monitoring and Time Dependent Analysis of Vertical Deformations of the Tallest Building in China", *Structural Control Health Monitoring*, 2017, vol. 24, no. 7, art. ID e1936; DOI: 10.1002/stc.1936.

[12] Y. Oshima, "Displacement Measuring Method, Displacement Measuring Instrument, Displacement Measuring Target and Civil Structure", Japan. US7535554B2.

[13] Z. Pióro, M. Osiniak, E. Antoszkiewicz, S. Wierzbicki, "Sposób pomiaru przemieszczenia pionowego elementów konstrukcji budowlanych", Poland. PL 239382, 08.09.2021.

Laserowo-inklinometryczna metoda pomiaru przemieszczeń w monitoringu konstrukcji

Słowa kluczowe: bezprzewodowy system monitoringu, inklinometr, laserowo-inklinometryczna metoda pomiaru, monitoring konstrukcji, monitoring ugięć i obrotów

Streszczenie:

W artykule przedstawiono metodę monitoringu konstrukcji z wykorzystaniem pomiaru przemieszczeń pionowych realizowanych optycznie, poziomo skierowaną wiązką lasera. Po przeglądzie literatury przedmiotu oraz analizie uwarunkowań stosowania typowych metod pomiaru przemieszczeń, ze szczególnym uwzględnieniem pomiaru prostopadłego do kierunku przemieszczenia, zaproponowano praktyczną aplikację metody w systemie monitoringu. Opracowano urządzenie pomiarowe ze zintegrowanym dalmierzem i czujnikiem inklinometrycznym służącym do korekcji wyników pomiarów dalmierzem w celu eliminacji błędów wynikających ze zmian przestrzennego położenia wiązki lasera. Rozwiązanie takie przyjęto jako alternatywne do bardziej złożonej i wymagającej metody, jaką jest stabilizacja położenia wiązki. Opracowana inklinometryczna metoda korekcji pozwala w prosty i czytelny sposób wyeliminować poważny problem metody pomiaru przemieszczenia prostopadle skierowaną wiązką lasera, jakim jest nieunikniony w praktyce brak trwałej stabilności położenia urządzenia pomiarowego. Opracowane urządzenie pomiarowe jest bezprzewodowe, zarówno w kwestii zasilania jak i komunikacji z pozostałymi elementami systemu monitoringu. Zastosowane czujniki inklinometryczne MEMS są indywidualnie kalibrowane, co pozwala na uzyskanie odpowiedniej dokładności pomiaru kąta obrotu wiązki lasera, zapewniającej precyzję korekcji wyników pomiaru ugięcia na poziomie poniżej 1 mm. W celu sprawdzenia poprawności pomiarów realizowanych przez opracowane urządzenie, przeprowadzono badania testowe w dwóch obiektach przemysłowo-magazynowych z funkcjonującymi systemami monitoringu wykorzystującymi inne metody pomiaru. W jednym przypadku istniejący system monitoringu bazowałna pomiarach kątów obrotu, w drugim zaś na bezpośrednich pomiarach ugięć pionowo skierowaną wiązką lasera. Testowane urządzenia zainstalowano w taki sposób, aby możliwe było bezpośrednie porównanie ich wskazań z pomiarami realizowanymi przez istniejące, wcześniej sprawdzone czujniki pomiarowe. Z przeprowadzonych badań wynika, że uzyskanie prawidłowych wyników pomiarów ugięć, skierowaną poziomo wiązką lasera wymaga wprowadzenia korekcji uwzględniającej przestrzenne zmiany położenia tej wiązki. Po odpowiedniej korekcji uzyskano zgodność ze wskazaniami istniejącego systemu na poziomie typowej dokładności systemu monitoringu konstrukcji, bazującego na przemieszczeniach. Badania potwierdziły, że zaproponowana metoda pomiaru przemieszczeń z inklinometryczną korekcją błędów wynikających z odchylania wiązki lasera od początkowego położenia, zapewnia dokładne i wiarygodne wyniki, pozwalając jednocześnie na uzyskanie dodatkowych informacji o zachowaniu się konstrukcji w miejscu instalacji urządzenia pomiarowego.

Received: 2022-07-02, Revised: 2022-08-12