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INCLINOMETER METHOD OF DISPLACEMENT MEASUREMENTS AS AN ALTERNATIVE TO OPTICAL MEASUREMENTS IN STRUCTURAL HEALTH MONITORING - LABORATORY TESTS

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The paper presents a method of structural monitoring with the use of angular displacement measurements performed with inclinometer devices. Inclinometer method is a solution free from the basic disadvantages of optical methods used commonly in structural monitoring, such as sensitivity to any type of visibility restrictions, pollution or influence of weather conditions. At the same time, with appropriate sensor parameters, a much better measurement accuracy is obtained than for typical optical methods and very low energy demand and moderate costs are achieved. Taking into account the above-mentioned issues, in the first stage an appropriate MEMS-type inclinometer sensor was selected, its laboratory tests were carried out and a method of the offset temperature drift correction, individual for each sensor, was developed.

Keywords: structural health monitoring, monitoring of deflections and rotations, inclinometer, wireless structural monitoring, low-cost monitoring system

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1. INTRODUCTION

The key issue to consider in relation to every civil structure is to ensure an appropriate level of structure safety at every stage of the investment, i.e. both in the design and construction phases as well as the entire operation period. Despite many procedures aimed at ensuring this safety, situations leading to structural failures or even collapses occur. Objects with light structure and flat roofs with large surfaces, such as warehouses, commercial buildings, industrial or exhibition halls are particularly exposed to such occurrences. Such events are the result of various factors, such as extreme weather conditions, undetected design or execution errors, and most often a combination of these factors. Among environmental actions, the causes of failures and collapses are usually excessive snow and ice loads, excessive wind loads or intense rainfalls. Issues of weather conditions and their influence on buildings have been discussed in many works, such as Geis et al. [2], Wardhana K., Hadipriono F.C. [13], Goliger et al. [5], Giżejowski et al. [3]. Research show that most collapses occurred in buildings with a lightweight, steel or wooden roof structure [2, 8, 14], which are characterized by a significant share of variable loads in total actions. Therefore they are sensitive to random, extreme climatic actions, and this sensitivity is additionally intensified by the common tendency to use increasingly economical and lightweight structure solutions. At the same time, we are dealing with increasingly visible climate changes manifesting, among others, various types of extreme weather events, such as heavy snowfalls, heavy rains and hurricane winds. All of these factors make the overloading of the structure and thus the threat to its security become likely.

In this context, it seems particularly reasonable to develop and apply some methods to monitor the behavior of structures under the influence of changing loads, which are particularly useful for the above-mentioned lightweight structures. The largest and most important part of the monitoring system is usually the set of measuring and transmitting devices installed in the facility. Depending on the type of structure and the resulting requirements for the monitoring system, as well as its limitations, displacements, deformations, dynamic characteristics, temperature or weather phenomena are most often monitored, and also vision methods are used [3, 4, 6, 7, 14-18]. In practical applications displacement measurements [3, 4, 6, 14, 16, 17] are most often used. They are characteristic for work of most structures, well reflecting their behavior under load, and at the same time they are relatively simple in measurements and interpretation. The second group of quantities, typical for monitoring systems, are strains, which allow to obtain information about changes occurring in specific places of the structure [4, 7]. However, they are sensitive to all kinds of local disturbances caused by, for example, secondary torsional moments or local bending, so it is more difficult to interpret them correctly. Monitoring of dynamic phenomena is needed only for some types of structures, such as roofs of stadiums, tensile structures or objects exposed to dynamic effects originating in transport [15]. Temperature monitoring usually has an auxiliary character and serves to compensate / correct the readings of sensors measuring other quantities [4, 7]. The monitoring of weather phenomena also plays a role in supporting the processes of assessing of other measurement results and forecasting the development of the situation [7]. Sometimes vision methods are even used. They can be used to monitor displacements, control critical structure sites, as well as to support observations of weather phenomena [4, 17].

An important feature of each monitoring system is the way in which particular system elements are connected and the manner of their powering [1]. In the traditional approach, wired connections of system devices as well as power supply from the power grid are used. This approach ensures stability and reliability of connections regardless of the surrounding conditions, but requires the distribution a large number of cables, which is especially costly and cumbersome to implement in large systems. In addition, the network of cables may hinder the ongoing operation of the facility. An alternative solution is the wireless system, in which communication between individual sensors and system devices takes place wirelessly (radio), and the power supply is from local batteries [3, 10, 14]. The limitation in the use of full system wirelessness can be a high energy demand of some devices, such as central units that manage system operation, which must be powered from the power grid. In case of wireless system, it is also necessary to take into account the necessity of periodic replacement of batteries, which requires access to devices and additional costs.

This paper presents the practical possibilities for wireless implementation of displacement measurements using inclinometers as an alternative to laser rangefinders. At start, the methods of displacement measurement used in practice are briefly discussed, with determination of their advantages and limitations, with particular emphasis on laser rangefinders and inclinometers. Next, the laboratory investigations of inclinometer sensors and the method of compensating their temperature drift are discussed. Finally, the conclusions from the conducted research are formulated.

2. DISPLACEMENT MONITORING METHODS

In practical applications of structural monitoring, the most common is the measurement of linear displacements, which reflect in a very good and direct way the behavior of the structural element / structure or a part of the structure. Laser rangefinders, total stations, hydrostatic level sensors, GPS techniques, inclinometers as well as vision methods are used for measurements in this type of systems. Each of these devices / methods has some advantages but also limitations, hence the possibility and legitimacy of their use is determined by the conditions in a given application.

Laser rangefinders have found a relatively wide application. These simple and inexpensive devices (with a measurement resolution at level of 1 mm), work very well in simpler solutions dedicated to typical objects and structures [3, 14]. However, classical laser rangefinder measurement face limitations that can hinder, sometimes even prevent the use of such method. The first problem is the need to measure the distance of the monitored structure point from a fixed place, which is associated with certain restrictions on the freedom in using of the object (the places where measurements are made cannot be obscured). The difficulty in using laser rangefinders is also the sensitivity of the rangefinder's optics to moisture and low temperatures - condensation or freezing on optical elements, water vapor will obscure the laser beam. Therefore, the condition of correct measurement is, in the case of this method, to ensure good visibility on the path of the laser beam, so the problems result primarily from the measurement method itself.

Another solution used to measure displacements in monitoring systems of building structures is the automatic total station [15]. One such device allows fully automatic measurements of displacements of many points located at a distance even up to 3500 m. This measurement method has similar limitations as laser rangefinders, i.e. good visibility is required between the total station and the measured points. In addition, taking into account the high costs of this device, such monitoring systems are usually based on individual total stations, which negatively affects their reliability. The sequential principle of measurements (with several dozen measuring points one cycle can take even several tens of minutes) also makes it impossible to obtain results from all points at the same time, which in turn makes difficulties to correctly interpret the measurement results for greater dynamics of load changes.

The method that can be used to measure displacements is GPS technology [15]. The disadvantage of this technique is, however, the low measurement accuracy, about +/-5 mm when measuring vertical displacements, which is insufficient for many typical building structures. The second major inconvenience is the necessity to constantly maintain paid licenses for the current provision of correction data from reference stations, without which the measurement results of GPS are incorrect.

The hydrostatic leveler [4, 15] works on a completely different principle. It is sometimes used in monitoring systems as a method with very high measurement accuracy, even up to 0.01 mm. It is a system operating on the principle of connected vessels, in which a number of devices that automatically measure the liquid level are connected to the hose level. It is therefore a cumbersome solution in installation and subsequent operation, hence, despite its simplicity, it has not found a wider application in practice.

One of the possibilities of measuring displacements in structure monitoring systems is the use of vision methods [17]. Here we have similar limitations as with the use of distance meters and total stations - the need to ensure adequate visibility between the camera and the place in which displacements are to be monitored. The cameras must also have a stable location throughout the entire monitoring period. In this method, the distance of the camera from the monitored point is also very important - with the increase of this distance the measurement accuracy decreases.

Another method used in structure monitoring systems is the measurement of angular displacements realized with inclinometers [16]. The principle of measurement, different from that of optical methods, means that there are no major disadvantages associated with these methods, such as the need to ensure good visibility or the problem of high humidity and low temperatures. In this case, the reference for measurements is the gravity vector, available anytime, anywhere. On the other hand, what arises in this solution is the issue of interpretation of the measurement results, which is usually more complex than with the methods discussed above.

3. THE CONCEPT OF USING INCLINOMETERS IN STRUCTURAL HEALTH MONITORING

Taking into account the possibilities and limitations of various displacement measurement methods in structure monitoring systems, attempts have been made to use angular displacement measurements using inclinometers as an extension of the classical displacement measurement method using laser distance meters. Bearing in mind the widest possible application of this method in practical applications, it was assumed that it should be an economically acceptable solution and adapted to work in wireless systems.

The measurement of linear displacements with laser rangefinders is effective in most typical applications in enclosed buildings, where there are no low temperatures, excessive humidity and pollution / dusting of the atmosphere limiting its translucency for the laser beam. In functioning systems, the most common solution is the displacement measurement performed as a measure of the change in the distance of the monitored structure point from a fixed building element located directly under this point, which means that a free space is required under the monitored point, most often on the floor. This, unfortunately, limits the freedom of operation of the facility in these places. Another issue is the lack of the possibility of using such a solution in facilities where such fixed places under the monitored points do not occur, such as in covered swimming pools, or where there are frequent changes in the arrangement of space under the structure, such as in sports and entertainment objects. Also the use of laser rangefinders in open buildings, such as canopy, is practically impossible due to the possibility of condensation and freezing of water vapor on the lenses at low temperatures.

Therefore, attempts were made to apply a different method of measuring and constructing the device free from the above-mentioned limitations - inclinometers were accepted for research and analysis. Sensors of this type are known and used in monitoring, but not in such applications as this paper concerns (monitoring deflections of roof structure).

To measure angular displacements, two types of inclinometer sensors can be generally used - with and without feedback. The first ones (with feedback) are very accurate, but they have a high price. This limits their application to very advanced and expensive monitoring systems. The inclinometers without feedback are much cheaper and they are potentially suitable for use in the typical monitoring systems.

The inclinometer sensors without feedback can be electrolytic or MEMS. After an analysis of the basic parameters of the pre-selected inclinometer sensors of these types, presented in Table 1, the MEMS sensor SCA103T was chosen for further research. In the first stage of development of the inclinometer device, the basic parameters of the selected sensor were analysed and compared with the parameters of typical laser rangefinders in terms of the requirements that result from their use in the discussed solution.

Table 1. Basic parameters of the selected inclinometer sensors

Parameter	Sensor type			
	Electrolytic		MEMS	
	SP5000-A-000	0717-4304-99	BMA180	SCA103T-D05
Range [°]	±45	±60	±90	±30
Resolution [°]	0.005 – 0.01	0.003	0.015	0.0004
Offset temperature drift [°/°C]	0.003 – 0.006	0.006	0.02	0.002
Slope temperature drift [%/°C]	0.1	0.1	0.01	0.005
Instability [°/h]	0.003	0.004	-	0.0000005

For the readability of the comparison results, it was assumed for the analysis that the monitoring will concern a typical single-span beam. In this case, with uniformly distributed load (q) and span (L), maximum values of deflection in the middle of the span (w_{max}) and rotation angle at the supports (φ_{max}) can be determined from the equation.

$$w_{max} = w\left(\frac{L}{2}\right) = \frac{5qL^4}{384EI} \tag{3.1}$$

$$|\varphi_{max}| = |\varphi(0)| = \frac{qL^3}{24EI} = 3.2\frac{w_{max}}{L} \tag{3.2}$$

where:

q – uniformly distributed load, E – elasticity modulus, I – moment of inertia, L – beam span.

In order for the sensor to be used to monitor a given structural element, its measurement accuracy must be at least an order of magnitude better than the maximum value of the monitored quantity. For this analysis, a beam with a span L= 20 m, typical for the main element of the roof structure of the industrial building, for which the limit deflection is L/250, was adopted, which in turn translates into a deflection permissible value of 80 mm. Assuming a typical situation for this type of buildings, when the monitoring concerns only snow loads, which is usually half of the total roof load, the deflection allowed from the standard snow load can be max. w_{perm} = 40 mm, and the allowed rotation angle of the beam end - φ_{perm} = 0.367°. In general, however, the designed cross-sections are not determined by the serviceability limit state (SLS), but the ultimate limit state (ULS), which means that the maximum deflection and rotation angles associated with the ULS will be lower than the given limit values.

Table 2 presents the basic parameters of a typical laser rangefinder used for measurements of vertical displacement. For such a device and the beam being analysed, the measurement error will typically be no more than 2.5%, maximum not more than 6.25%. It can be assumed that this is an acceptable value for typical structure, for which the safety coefficients resulting only from partial factors for actions are of the order of 1.5.

Table 2. Basic parameters of typical, manual laser rangefinders

Parameter	Determination method	Value
Operating temperature*		0 ÷ +50°C
Measurement time		0.5÷2 sec
Power consumption during measurement	Average value	600 mW
Measurement resolution		1 mm
Measurement accuracy**	Typically	±1.5 mm
Relative measurement resolution	$1\text{mm}/w_{perm}$	2.5%
Relative measurement accuracy	$1.5\text{mm}/w_{perm}$	±3.75%
Total relative measurement accuracy	$(1+1.5)\text{mm}/w_{perm}$	±6.25%
* Typical operating temperature range for laser rangefinders is -10 to +50°C. At low temperatures, the optical system of the device can be frosted. ** Error caused, for instance, by change of substrate illumination.		

The first stage of the analysis is to check whether it is possible to obtain a comparable measurement accuracy when using the previously selected inclinometer sensors SCA103T. The current inclinometer measurement result can be given by the formula:

$$y(T) = y_{offset}(T_{ref}) + TC_{offset} \cdot (T - T_{ref}) + Slope(T_{ref}) \cdot x + TC_{slope} \cdot (T - T_{ref}) \cdot x \tag{3.3}$$

where:

T - current temperature [°C], x - current value of measured inclination [°], T_{ref} - temperature in which the reference measurement was performed [°C], y(T) - current inclinometer reading [°], $y_{offset}(T_{ref})$ - offset at temperature T_{ref} [°], TC_{offset} - offset temperature drift [°/°C], $Slope(T_{ref})$ - inclinometer slope at temperature T_{ref}, TC_{Slope} - slope temperature drift [/°C],

The error resulting from the offset and the slope temperature drifts for the initial (reference) inclination angle x_b and temperature T is thus equal:

$$\Delta y(T, x_b) = (T - T_{ref}) \cdot (TC_{offset} + TC_{Slope} \cdot x_b) \tag{3.4}$$

Table 3 presents the values of the basic parameters of the selected SCA103T sensor, important in the context of structural monitoring. Assuming that the permissible measurement error is to be comparable to a typical measurement error of the rangefinder, i.e. around 5% of the limit value, and that the measuring range is equal $\varphi_{perm} = 0.4°$ ($\varphi_{perm} = 0.367° \approx 0.4°$), with the typical value of the offset temperature drift ±0.002°/°C, the maximum temperature range at which the SCA103T sensor could operate is only ±10°C. This is much smaller than the anticipated working range of the inclinometer (-20°C ÷ + 60°C). To estimate the necessary parameter values of the sensor, one can assume that half of the permissible measurement error may result from the offset temperature drift and the other half from the slope temperature drift.

Half of the permissible error, i.e. $0.5 \cdot 0.05 \cdot 0.4° = 0.01°$ (for ±40°C), gives the necessary offset drift not greater than ±0.00025°/°C, which is almost ten times less than the typical offset drift of the sensor being discussed. Such a low value can only be achieved by applying software compensation (Table 3) individually for each sensor. In the case of the discussed sensor, this approach is justified due to its high stability in time resulting from its structure - the seismic mass suspended on springs is made of monocrystalline silicon, a material very stable mechanically, thermally and long-term.

The second half of the permissible measurement error, i.e. also 0.01° (for ± 40°C), may be due to the slope temperature drift. For the slope temperature drift of the SCA103T sensor, equal 50ppm/°C, achieved after using external software compensation, according to the manufacturer's recommendations, this value of the permissible measurement error can be obtained for an initial slope of 5° ($(50\text{ppm}/°\text{C})\cdot(\pm 40°\text{C})\cdot 5° = \pm 0.01°$). In practice it is possible to leveling the inclinometer with an accuracy much better than 5°, so we will not need individual compensation for the slope temperature drift of the sensor. The accuracy of the sensor leveling better than 1° (easily achievable in practice) will result in a reduction of the requirements set for the permissible value of the offset temperature drift or will reduce the permissible measurement error to the level of 2-3%.

Table 3. The SCA103T sensor characteristics

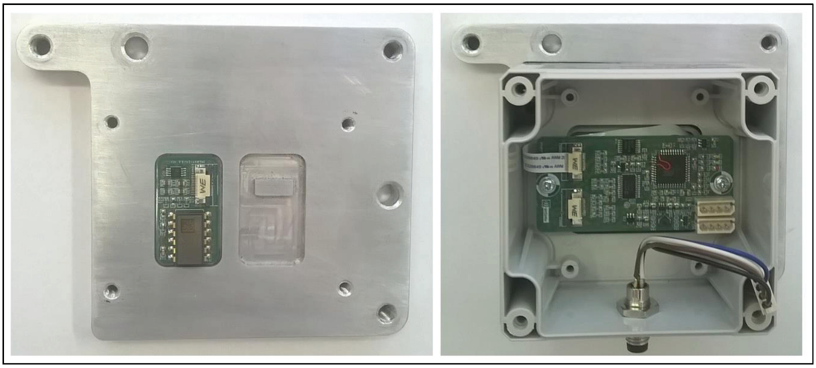
Parameter		Value (typically)
Operating temperature		-40°C ÷ +125°C
Absolute measurement resolution (noise spectral density $\cdot\sqrt{\text{bandwidth}}$)	Bandwidth = 5Hz	0.001°
	Bandwidth = 1Hz	0.0004°
	Without external filtration	0.002°
Measurement time**	Bandwidth = 5Hz	0.4 sec
	Bandwidth = 1Hz	1.6 sec
	Without external filtration	10 ms
Power consumption (MEMS sensor + microcontroller)		60mW (3V, 10mA + 10mA)
Offset temperature drift	typically	±0.002°/°C
	Software-compensated***	±0.0002°/°C
Slope temperature drift	typically	±130ppm/°C
	Software-compensated****	±50ppm/°C
Relative measurement resolution: resolution/φ_{perm}	Bandwidth = 5Hz	0.27%
	Bandwidth = 1Hz	0.11%
	Without external filtration	0.54%
Long-term stability*****		0.036°/10 years

* The operating temperature range is not limited by sensor parameters (-40 ÷ +125°C), but by practical requirements.
** With standard, linear filtration applied.
*** Software compensation using polynomial whose factors are determined based on the measurement results - the average catalog value equals to ±0.0002°/°C.
**** Software compensation with a company's polynomial.
***** Stability determined from accelerated aging tests (HTB) for SCA61T series sensors.

The presented considerations show that it is possible to use an inclinometer device with the SCA103T sensor in monitoring systems, even in temperature range from -20°C to + 60°C. However, ensuring the quality of measurement not worse than with the laser rangefinders, requires individual compensation of the offset temperature drift of the SCA103T sensor. Such an inclinometer will be much more energy-efficient than the rangefinder - in measurements without additional filtration it consumes even 1000 times less energy than the rangefinder – it is extremely important in wireless systems, allowing very long periods of work without replacing the battery.

4. LABORATORY TESTS OF THE INCLINOMETERS

In order to perform laboratory tests to examine the metrological properties of the inclinometers with the SCA103T sensor and to develop the procedure of offset drift compensation for this sensor, a prototype of the two-axis inclinometer IM103T (Inclinometer Module), shown in Fig. 1, was developed. The base plate of the Inclinometer Module with the SCA103T sensor mounted on the PCB (one axis) is shown in Fig.1a, and the open case of the device with complete electronics is shown in Fig. 1b. The tests were carried out in the chamber type ILW115-W STD (manufactured by POL-EKO APARATURA) with temperature regulated in the range -15°C ÷ + 70°C [9].



(a) (b)

Fig. 1. The prototype of the two-axis Inclinometer Module IM103T with SCA103T sensors

For increasing the stability of the test stand, and thus increase the accuracy of the determined polynomial coefficients to compensate the offset temperature drift, a granite base plate was used in the thermal chamber where the measurements of Inclinometer Modules were made.

The inclinometer SST460-15 [12], built on the basis of the SCA103T sensor, using special producer's calibration and compensation procedures, was used to control the mechanical stability of the test stand. Testing of the stand with this inclinometer showed a output temperature drift at the level of 0.0005-6º/°C, thus within the producer's inclinometer specification (≤0.0006°/°C), hence the conclusion that temperature stability of the stand is at a sufficient level for research.

In the first stage of the laboratory tests of the inclinometer prototype at temperature change of -15°C ÷ + 70°C, very large changes in inclination in the range of high temperatures in the first cycle of temperature changes were observed, which do not repeated in subsequent cycles. It was assumed that this was the effect of thermal relaxation of the milled steel inclinometer base and PCBs. It was assumed, therefore, that the produced inclinometers will be obligatory annealed at temperature not lower than 70°C.

In the next stage of the research, the noise properties of the IM103T prototype were measured. Their goal was to check whether the noise of the prototype is consistent with the specification of the SCA103T sensor used. At the 1 Hz measuring bandwidth, the noise was obtained with an effective value of 0.00039º for the Y axis and 0.00048º for the X axis respectively. The manufacturer specifies the spectral noise density of the SCA103T sensor at 0.0004º/√ Hz, i.e. the effective value equal 0.0004º for the 1 Hz bandwidth. The measured noise values are slightly higher due to the work of the fan and compressor of the cooling chamber. It was therefore possible to conclude that the measurement results confirm the manufacturer's noise specification.

The main stage of the laboratory tests was aimed at testing the offset and slope temperature drifts of the inclinometer. First, the dependence of the output signal offset on temperature was examined. In order to eliminate the influence of the sensor's slope drift on the results, the tests were carried out at inclination angles close to zero. The conducted research shows that the temperature drift of the tested model does not exceed -0.001°/°C for the X axis and + 0.002°/°C for the Y axis (Fig. 2), and therefore it is within the range specified by the manufacturer as ±0.002°/°C (Table 3). Moreover, what is very important in the context of the possibility of introducing compensation, the dependence of the offset on temperature is monotonic and can be approximated by relatively low order polynomials - Fig. 2 shows the approximation by 4th order polynomials.

Next, the influence of the slope temperature drift of the sensor on the measurement results was examined by measuring the dependence of the output signal on temperature for large inclination angles. An exemplary relationship for the inclinometer's X axis is shown in Fig. 3, wherein this relationship taking into account both the effect of the offset and slope temperature drifts. In order to separate the influence of these two quantities, the following operations were carried out. Numerical compensation of the slope temperature drift with the company's polynomial [11] has been made:

$$S_{corr} = -0.0000005 \cdot T^3 - 0.00005 \cdot T^2 + 0.0032 \cdot T - 0.031 \tag{4.1}$$

Compensated in such a way dependence of the output signal on temperature is also shown in Fig. 3.

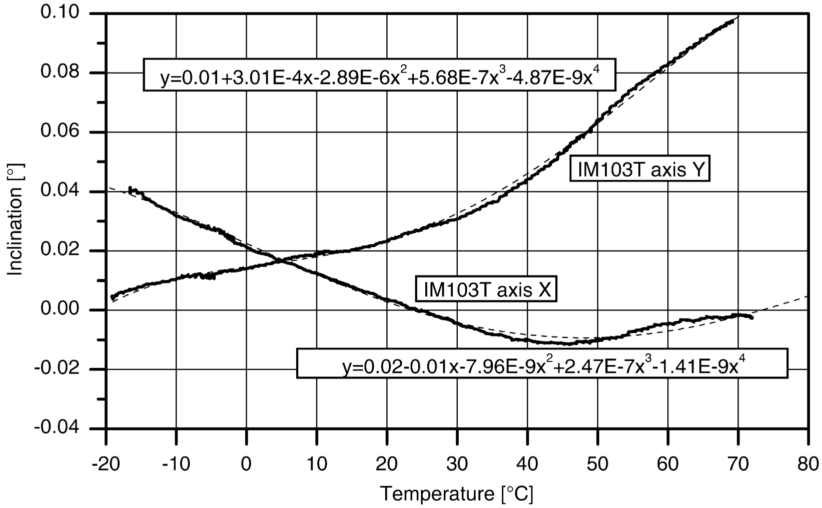


Fig. 2. Measured dependence of the prototype of IM103T Inclinometer Module offset on temperature

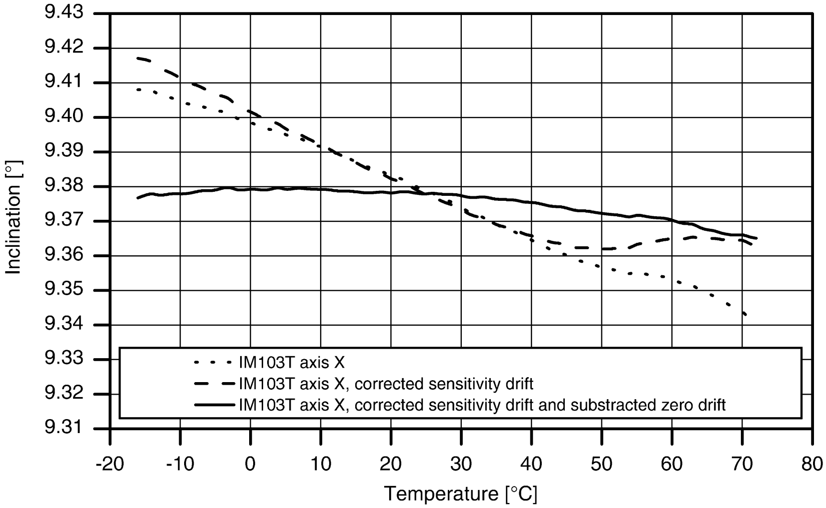


Fig. 3. Compensation of the offset and slope temperature drift for the prototype of IM103T Inclinometer Module

Then, from the compensated characteristic, the dependence of the offset temperature drift, shown in Fig. 2, was subtracted. The corrected in such a way dependence of the output signal on the angle for inclination of 9° is also shown in Fig. 3. It meets predefined requirements for temperature stability - within temperature range -20°C ÷ + 60°C the measurement error does not exceed ± 0.008°, i.e. not more than ± 0.0002°/°C.

Sample of measured dependences of the inclination angle on temperature and their approximation with the use of 4th order polynomials for 4 inclinometers are shown in Fig. 4.

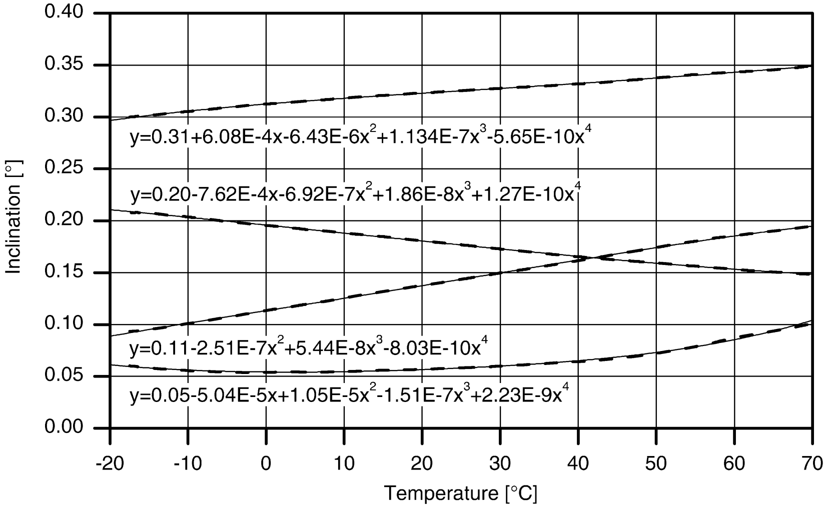


Fig. 4. Approximation of the measured dependence of the inclination angles on temperature by 4th order polynomials for 4 pcs of inclinometers

The determined polynomials are then used to compensate inclinometer readings, during which temperature changes in the slope of the measuring plate are taken into account and the offset correction is performed in such a way that the inclinometer indicates 0 for the horizontal position. Fig. 5 shows the results for an exemplary inclinometer after such a correction - as it can be seen, the stability of zero has been achieved at a level better than 0.0005° in the full temperature range, which meets the need for inclinometers in structural monitoring systems. At the same time, a one-point calibration of the internal temperature sensor of the SCA103T sensor is carried out, as recommended by the sensor manufacturer. Temperature measurement in the climatic chamber is used as a reference.

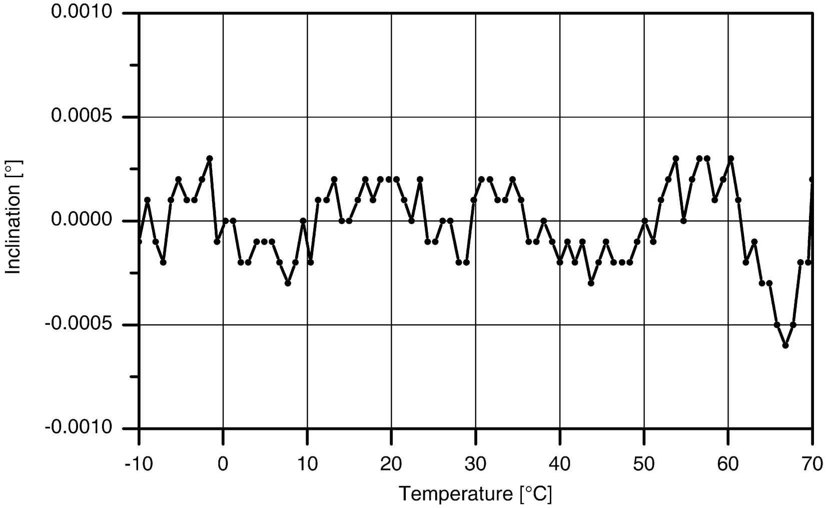


Fig. 5. Temperature stability of the inclinometer zero after numerical compensation of the offset temperature drift

5. CONCLUSIONS

The goal of the work described in this paper was to develop a new method of monitoring displacements of structure, based on measurements of rotation angles, which would be an alternative and complement to typical optical methods using, for example, laser rangefinders. This method was supposed to eliminate the main disadvantage of optical methods, i.e. the requirement to ensure adequate visibility on the path of the laser beam, which is particularly troublesome in outdoor installations exposed to below zero temperatures and high humidity as well as high pollution. An important criterion for choosing the solution was also the price - it must be low cost because it is primarily dedicated to be used in simple systems designed to monitor typical structural systems, such as industrial building structure. Another feature that should characterize the method is low energy demand, enabling it to be used in wireless systems.

These features are characteristic to the method based on the measurement of rotation angles using inclinometers. The reference for measurement in this case is gravity vector, so all aspects related to visibility are irrelevant. The use of MEMS sensors allows, after using the offset temperature drift correction procedure, to obtain the required measurement accuracy at an acceptable price of the sensor and thus also the complete device. The energy consumption is so moderate that the sensor can work for many years without replacing the battery, even at today's level of development of battery power sources. This feature also allows to reduce system maintenance costs, which in practice may be limited to battery replacement every few years, in contrast to optical devices which require more frequent inspections to ensure proper optics cleanliness.

The laboratory tests showed very good metrological properties of the used sensor and its usefulness in the measurement method being developed. The designed device is characterized by a very good, in the context of its intended use, resolution of the measurement, by an order of magnitude better than in the case of typical laser rangefinders.

The results of analyses and tests carried out so far allow to state that the measurement of rotation angles using MEMS inclinometers is a good, better than traditional optical methods, solution for monitoring displacements of structures. The next stage of research will be testing the measuring method and the inclinometer device in the practical application of monitoring the structure of the functioning facility.

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LIST OF FIGURES AND TABLES:

INKLINOMETRYCZNA METODA POMIARU PRZEMIESZCZEŃ W MONITORINGU KONSTRUKCJI JAKO ALTERNATYWA DLA OPTYCZNYCH METOD POMIAROWYCH - BADANIA LABORATORYJNE

Słowa kluczowe: *monitoring konstrukcji, monitoring ugięć i obrotów, inklinometr, bezprzewodowy monitoring konstrukcji, niskokosztowy system monitoringu*

STRESZCZENIE

W artykule przedstawiono metodę pomiaru przemieszczeń kątowych, realizowanych przy pomocy inklinometrów, jako alternatywę do stosowanych w monitoringu konstrukcji optycznych metod pomiarowych. Po krótkim wprowadzeniu dotyczącym ogólnie zagadnień monitoringu konstrukcji, przeprowadzono analizę metod pomiarowych stosowanych w systemach monitoringu, ze szczególnym uwzględnieniem pomiarów przemieszczeń oraz zalet i wad tych metod. Z analiz tych wynika, że rozwiązaniem wolnym od głównych wad typowych metod optycznych są pomiary inklinometryczne. Są one niewrażliwe na wszelkiego typu ograniczenia widoczności, zanieczyszczenia czy oddziaływania atmosferycznie, a bazą dla pomiarów jest wektor grawitacji, dostępny zawsze i wszędzie. Przeprowadzono analizę dostępnych rozwiązań czujników inklinometrycznych, mającą na celu wytypowanie sensora pozwalającego na uzyskanie odpowiedniej dokładności pomiarów przy umiarkowanych kosztach urządzenia i małym zapotrzebowaniu na energię, co jest szczególnie ważne w przypadku planowanego zastosowania czujnika w systemach bezprzewodowych i wpisuje się w powszechną tendencję do oszczędzania energii. Mając na względzie powyższe kwestie dobrano odpowiedni sensor inklinometryczny typu MEMS i przeprowadzono testy laboratoryjne jego właściwości metrologicznych przyjmując, że musi on zapewniać dokładność porównywalną do typowych czujników laserowych - przyjęto, że błąd pomiaru nie może być większy niż 5%. W tego typu czujnikach błędy pomiaru wynikają w głównej mierze z temperaturowego dryftu czułości i dryftu offsetu. Analizy i testy wykazały, że przy zastosowaniu tylko zewnętrznej kompensacji programowej czujnika, można uzyskać temperaturowy dryft czułości sensora na poziomie 50ppm/°C, co oznacza że błąd pomiaru będzie nie większy niż ±0.00025°/°C nawet przy nachyleniu początkowym inklinometru rzędu 5°. Zakładając, że połowa z założonego maksymalnego błędu, równego 5%, będzie "przeznaczona" na dryft czułości, czujnik może być stosowany nawet w zakresie temperatur ±40°C, a więc całkowicie wystarczającym z punktu widzenia systemu monitoringu. Inaczej przedstawia się sytuacja w przypadku błędu wynikającego z temperaturowego dryftu offsetu - standardowa wartość dryftu offsetu wynosi ±0.002°/°C, a więc jest prawie dziesięciokrotnie większa od wymaganej (±0.00025°/°C). Jest tu więc konieczna indywidualna kompensacja programowa dla każdego sensora. W celu opracowania metody tej kompensacji, każdy sensor był badany w odpowiednio przygotowanej i przetestowanej przy pomocy inklinometru wzorcowego, komorze termicznej. W celu wyeliminowania wpływu dryftu czułości sensora na wyniki, badania prowadzono przy kątach nachylenia inklinometru bliskich zeru. Zmierzone zależności kąta nachylenia od temperatury były aproksymowane indywidualnie dla każdego czujnika, wielomianami 4-go stopnia, które następnie były wykorzystywane do kompensacji wskazań inklinometrów. Po takiej korekcji uzyskiwano stabilność zera na poziomie lepszym niż 0.0005° w pełnym zakresie temperatury, co spełnia z nadmiarem zakładane wymagania i potrzeby zastosowania inklinometrów w systemach monitoringu konstrukcji. Następny etap badań to testowanie skalibrowanych czujników w badaniach "In-situ", w monitoringu konstrukcji funkcjonującego obiektu - zostaną one przedstawione w innym artykule.

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