ARTICLE

EVALUATION OF THE ACCURACY OF THE PHASE METRIC METHOD OF GONIOMETRIC CONTROL IN GEOTECHNICAL MONITORING

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ABSTRACT

The relevance of the study is due to the increasing requirements for observing the measuring accuracy and sensitivity of the control of angular parameters (goniometry) in the process of angular moving of the geotechnical monitoring objects. It is shown that the use of accelerometers is a promising approach in the field of dynamic goniometry. However, the stringent requirements for observing operating conditions and the low noise immunity of accelerometers do not provide the possibility of large-scale implementation of these sensors. In this regard, this article is aimed at studying the accuracy of the new method of automated measurement of the angle based on accelerometers, which will compensate for the existing errors of the accelerometer sensors. As a method of processing the signals of the accelerometers, it is proposed to use the phase metric method, the essence of which is to convert the signals of the accelerometers into a harmonic function of time and calculate the phase shift proportional to the angle of rotation of the accelerometer. The article substantiates the use of the phase metric method in measuring accelerometric systems, presents the results of experimental studies evaluating the accuracy of the developed method, as well as the results of testing the sensor on real monitoring objects. The materials of the article are of practical value for specialists in the field of measurement automation, geotechnical monitoring, as well as specialists in the development of tools and methods for optimizing the metrological support of inertial sensor systems.

KEY WORDS
Geo technical monitoring, goniometric control, phase metric method, accelerometers

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INTRODUCTION

Registration and control of the angular motion parameters of construction objects and their components is an urgent metrological task of geotechnical monitoring. The development of tools and methods for monitoring the angular parameters of objects is becoming increasingly important with increasing requirements for compliance with measuring accuracy and sensitivity. For example, during geotechnical monitoring, to monitor the spatial characteristics of buildings are monitoring tools (tilt meters) that allow you to track changes in the spatial state and geometric parameters of the structure. They are equipped with various types of sensors: solid-state accelerometer, compensated servo-accelerometer, electric DTE converter, etc. [1]. Depending on the type of specific tasks and the typology of geotechnical control objects (hazardous facilities, industrial facilities and residential buildings), tolerances for vertical deviations of buildings and structures vary in the range from 0.3° to 5(7) °. In this case, the geometrical systems of geotechnical monitoring must meet the requirements of high sensitivity (<0.3°) and noise immunity (> 0.1°) of measurements.

An example of equipment used to monitor building vibrations is the Guralp CMG3ESPC [2] and the Guralp CMG-5T accelerometer [3]. The use of accelerometers as an informative measurement method is characterized by low temperature stability, has severe restrictions on the scale of the observational network, and requires additional adjustment of measurements taking into account exogenous loads. The basis for calculating the slope angle when processing information in systems of this class is the standard trigonometric transformation of the projections of the gravitational acceleration vector on the corresponding sensitivity axes of the sensor. In special cases, numerical integration and wavelet transform of the recorded signals are also used. In this case, the main drawback is that the data on changes in spatial and geometric characteristics show only the final result of the structural deformation, but do not reflect the real process of the development of these deformations.

When using accelerometers in goniometric control, there are a number of metrological problems. It is known that the largest numerical component of the total error of the accelerometers is the zero error and the sensitivity error - 10% and 6% each, as well as the lateral sensitivity error (2 ... 5%) and non-linearity of the accelerometer (0.5 ... 2.5%). Also significant disadvantages of these inertial sensors are the relatively low accuracy and noise level of the output signal, zero drift [4]. In this case, the total error determined from the mean square criterion reaches 12-15% [5]. This error value is very large; therefore, to increase the accuracy of measurements, it is necessary to apply methods for compensating for accelerometer errors.

The multiplicative errors of the accelerometer transducers should be distinguished as a separate class of errors that have a major effect on the stability of the measuring branches of the transducer. In the theory of errors, the multiplicative error is defined as a deterministic systematic deviation of the readings of the

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measuring device with a long period [6, 7]. The causes of the multiplicative error are mainly the peculiarities of the operating environment (temperature instability, instability of the supply voltage source, etc.) [8-11]. Moreover, the multiplicative component of the measurement error depends both on the projection of the apparent acceleration on the nominal axis of the sensitivity of the accelerometer (the error of the scale factor), and on the projection of the apparent acceleration on the plane orthogonal to the nominal axis of the sensitivity of the accelerometer (the error of the mismatch of the axes).

As a solution to the problem of increasing the stability of measurements to the influence of multiplicative errors, compensation methods are widely used, the essence of which is the use of an alternating current source in devices for generating the output signal of the accelerometer with subsequent amplification of the rectified output signals in differential-type amplifiers. In this case, accuracy is improved and instability is eliminated by incorporating into the measuring circuit a variable compensation resistor, one of the contacts of which is connected to the input of one of the rectifiers, the other with an additional input of a differential amplifier [12].

There is a known fact about the direct dependence of the maximum mismatch of the branches of the accelerometer transducer at the maximum value of the multiplicative error. In this case, the multiplicative error cannot be fully compensated, and it can be partially eliminated by compensating for the asymmetry of the differential measuring transducer [13].

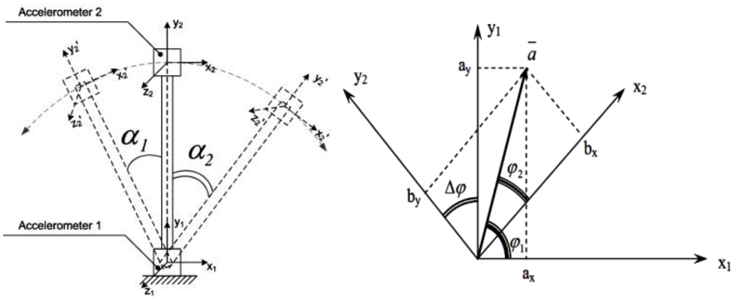
Currently, on the basis of improving the technological base and taking into account the foregoing, we can conclude that there are prospects for the widespread use of accelerometric converters. Analysis of the operational properties of accelerometric converters (Analog devices, Motorolla, Seika, STM microelectronics, Honeywell, etc.) [14-17] shows that the manifestation of dominant errors has low consistency, a lack of algorithmic support (lack of data processing requirements, unreliability of compensation mechanisms) and design features (misalignment of the sensitivity axes to the converter housing). Therefore, the development and use of data processing methods for accelerometers require not only the need for development, but also the development of algorithms.

The aim of the study is to assess the accuracy of the phase metric method of goniometric control based on the use of accelerometers, which allows you to compensate for the existing errors of the accelerometer sensors and improve the metrological characteristics of the accelerometer systems for monitoring the angular displacements of objects.

METHODS

Phase metric method of accelerometric measurements

The proposed phase metric method of accelerometric measurements assumes the presence of at least a pair of accelerometers mounted coaxially in the area of the control object that performs angular motion. [Fig. 1a] show variations of the layout schemes for attaching accelerometric sensors to the test object using the phase metric method. [Fig. 1b] illustrates the determination of the rotation angle of two accelerometers based on the projections of the acceleration vector of gravity onto each of the axes of the accelerometers in a rectangular coordinate system in two-dimensional space.



a) b)

Fig. 1: Phase metric method of accelerometric measurements.

To implement the accelerometric measurements of the angle using the phase measuring method, it is necessary to convert the signals from three-component accelerometers to the phase of the sinusoidal oscillation, multiplying them by and. The most detailed implementation of the phase metric method of accelerometer measurements of the angle is presented in [Fig. 2].

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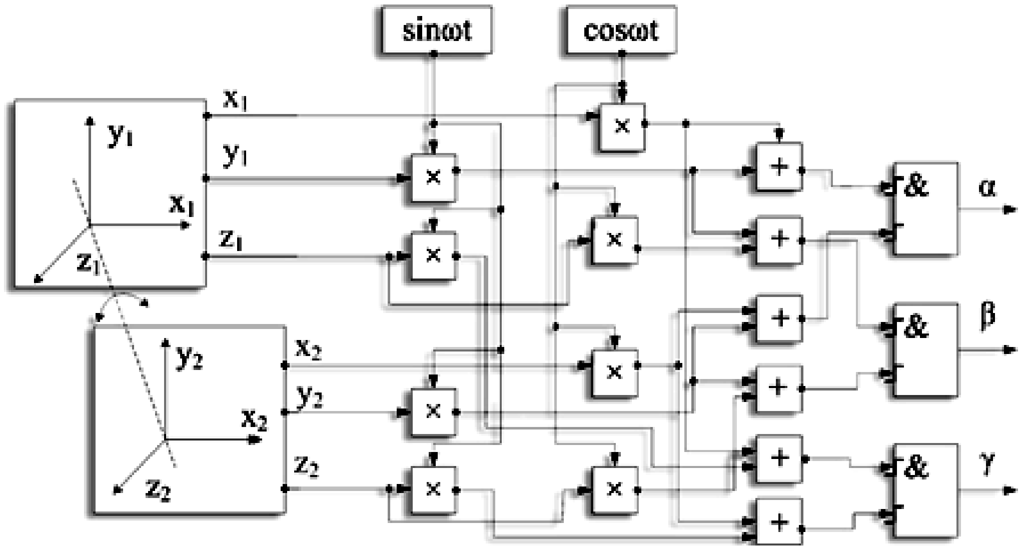

Fig. 2: Block diagram of the phase-measuring method of accelerometer measurements of the angle.

As a result of the multiplication operation, the signals of the accelerometers will take the form:

$$x_1 = k_{x1} a\cos(\Delta\alpha);\quad y_1 = k_{y1} a\sin(\Delta\beta);\; z_1 = k_{z1} a\cos(\Delta\gamma);$$
$$x_2 = k_{x2} a\cos(\Delta\alpha);\quad y_2 = k_{y2} a\sin(\Delta\beta);\; z_2 = k_{z2} a\cos(\Delta\gamma); \qquad (1)$$

where are the angles between the direction of the acceleration vector $\vec{a}$ of the common point O located on the axis of rotation and measuring accelerometric systems ($(\vec{x}_1, \vec{y}_1, \vec{z}_1)$ and $(\vec{x}_2, \vec{y}_2, \vec{z}_2)$); $k_{x1}, k_{y1}, k_{z1}\ k_{x2}, k_{y2}, k_{z2}$, , , are the sensitivity coefficients of the corresponding accelerometers.

The formula for the product of the total signal for the components x and y of the accelerometer 1 and accelerometer 2 is:

$$S = \sum U_1 \cdot \sum U_2 = \frac{1}{2}(\cos\alpha - \cos(2\omega t + \varphi)) \cdot U^2 \cdot \sqrt{{x_1}^2 + {y_1}^2} \cdot \sqrt{{x_2}^2 + {y_2}^2} \qquad (2)$$

where φ is the phase shift.

Since double the frequency is observed in the signal as a result of transformations according to formula (2), further signal conversion involves the use of a low-pass filter (LPF) and separation of the phase angle that is practically equal to the angle of goniometric control. When implementing the algorithm for calculating the phase angle by converting it to a time interval, the error of the method can be estimated.

Assuming frequency multiplicity, the ratio of the generator frequency and the sampling frequency:

$$\frac{F}{f_d} = m \qquad (3)$$

The error of determining the angle in this case, for the real value of the phases based on direct calculations:

$$\alpha = arctg\left[\frac{U^0{}_i \sin(2\pi \cdot m)}{U^0{}_{i+1} - U^0{}_i \cos(2\pi \cdot m)}\right] - arctg\left[\frac{U_i \sin(2\pi \cdot m)}{U_{i+1} - U_i \cos(2\pi \cdot m)}\right] \qquad (4)$$

In this case, the analytical expression for estimating the angle measurement error by means of the accelerometric method is as follows:

$$max(\Delta\alpha/\alpha) = \frac{\sqrt{2\pi \cdot m - 1} - arctg(\sqrt{2\pi \cdot m - 1})}{\pi \cdot m} \qquad (5)$$

As can be seen from expression (5), there are no multiplicative components in the error structure, and the systematic error in determining the angle can be reduced by increasing the sampling frequency with respect to the generator frequency.

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RESULTS AND DISCUSSION

Application of the phase metric method in geotechnical monitoring

In the field of geotechnical monitoring, accelerometers were used to record the angle of deviation from the vertical of the supporting structures of the building and horizontal subsidence of the foundation [18 - 20]. The principle of operation of the sensor in the field of geotechnical monitoring is based on determining the rotation of load-bearing structures and subsidence of the foundation of buildings and structures from the vertical in various planes and determining the angle of axial deviation relative to the base coordinate system associated with the Earth [21]. In this case, it is advisable to carry out joint monitoring of the hydrogeological regime [22, 23] and deep geodynamic processes [24] using approaches to select key geodynamic objects [25].

The object of research using the developed method was the design of a separate two-story three-section building of a residential brick house. The relief of the building plot is calm, the layout is approaching horizontal. The building is two-story, rectangular in plan, with a basement and an attic. Basement floor height (from floor to ceiling) - 1,500m. The height of the first and second floors (from floor to ceiling) is 2,700m. The general dimensions of the building are 46,900 x 12,000m. The maximum height of the building from the planning level is 9,700m. According to the structural system, the building of this residential building belongs to wall buildings. The structural design of the building is frameless longitudinal wall. Vertical load-bearing structures - brick walls (from mark-0.800 to mark + 6.300); horizontal supporting structures - prefabricated reinforced concrete floor slabs (overlapping basement, first and second floors).

As a result of the initial visual inspection, it was revealed that the wall of the building has a drawdown of up to 103 mm. In addition, visually detectable deformation fractures of the building located in the middle of the building were discovered. Vertical, horizontal and inclined through cracks in the outer brick walls of the building with an opening width of up to 18mm. Deformations and subsidence of building foundations as a result of the formation of voids (up to 250 mm deep) in a soil base under precast reinforced concrete slabs of a strip foundation. Vertical and inclined through cracks in the internal brick walls of the building with an opening width of up to 16 mm.

The layout of the accelerometers (LIS331DLH, STMicroelectronics) for geotechnical monitoring of the deformation processes of the foundation and load-bearing walls of a residential building is shown in [Fig. 3] [26].

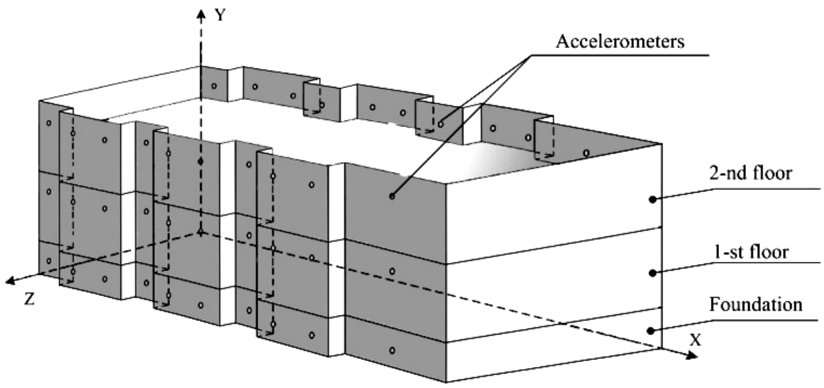

Fig. 3: Layout of accelerometer sensors.

An experimental assessment of the accuracy of the phase metric method during geotechnical monitoring

The changes in the foundation settlement were recorded simultaneously with the changes in the angle of inclination of the foundation parts at the control points. Before the onset of operational observations, a metrological assessment of the accuracy of the phase metric system of goniometric control was carried out using a Leica NA532 optical level meter. This model is equipped with a compensator and air damper system and has high sensitivity. Automatic alignment of the device to the working position occurs in the compensator's operating range of 15´ with an accuracy of ± 0.5 ". [Table 1] shows the results of an experimental assessment of the accuracy of the phase-measuring method compared to the applied goniometric control method.

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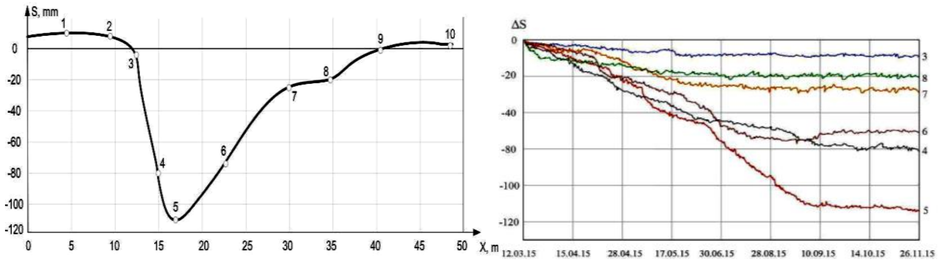
Table 4: Results of an experimental assessment of the accuracy of the developed method

The angle of rotation of the shaft according to the readings of the LeicaNA532, °	The average value of the angle of rotation obtained by the traditional method,°	The average value of the rotation angle obtained on the basis of the developed method, °
1±0,00012	1,0256	1,0021
2±0,00012	2,0183	2,0054
5±0,00012	5,0197	5,0012
8±0,00012	8,0249	8,0063
10±0,00012	10,0317	10,0023
12±0,00012	12,0299	12,0088
15±0,00012	15,0317	15,0097

[Fig. 4] shows the distribution of sediment values along the perimeter of the foundation at the time of the beginning of monitoring and the results of data on the control points of observations in the period from 12.03.2015 to 11.26.2015.



a)

b)

Fig. 4: a) The initial distribution of sediments along the perimeter of the foundation, b) a graph of changes in precipitation in the places where the sensors are installed.

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CONCLUSION

The results of an experimental evaluation of the accuracy of the method show that, on average, the deviation of the measured values of the angle from the value of the angle of rotation when processing the data by the developed method of goniometric control is 0.0053°. When processing data using the traditional trigonometric transformation using the arc tangent function of 0.0260°. The results of testing the sensor based on the developed method for geotechnical monitoring made it possible to estimate the error with respect to theodolite measurements. The error amounted to (± 0.01 deg), the accuracy of registration of the foundation settlement (± 0.1 mm).

As a result of the research, an analysis was carried out and methods for reducing the errors of accelerometric transducers in solving problems of measuring angles were proposed. According to the results of the analysis, it was proposed:

- reduce the total value of the error by software tools to compensate for errors.
- the errors of zero offset and temperature drift are compensated by the method of removing the systematic component from the acceleration signal;
- the error of nonlinearity and the error of the bias of the sensitivity coefficient of the accelerometer are compensated by the calibration method of the accelerometer in the reduced range of measured accelerations;
- to eliminate multiplicative errors due to the application of the developed phase-measuring method for measuring the angle of rotation.

As a result of research, a new method for automated measurement of the angle based on accelerometers was developed and tested. It has been established that in the case of applying the phase metric method, the measuring error of the accelerometer transducers can be significantly reduced and amount to degrees with the sensitivity coefficient of the accelerometer. This will improve the metrological characteristics of accelerometer measuring systems.

CONFLICT OF INTEREST
There is no conflict of interest.

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REFERENCES

[1] Kuckartza J, Collier P, Hutchinson G. [2011] The Design of an Integrated Structural Monitoring System for a High-Rise Building Based on Tiltmeters and GNSS. Joint International Symposium on Deformation Monitoring. http://dma.lsgi.polyu.edu.hk/JISDM-Proceeding/Proceeding/Full%20paper/164.pdf.

[2] Guralp Systems CMG-3ESPC User Manual http://www.manualsdir.com/manuals/770943/guralp-systems-cmg-3espc.html?download

[3] Guralp Systems CMG-5T User Manual http://www.guralp.com/documents/DAS-050-0001.pdf.

[4] van Hees VT, Fang Z, Langford J. et al. [2014] Auto-calibration of accelerometer data for free-living physical activity assessment using local gravity and temperature: an evaluation on four continents, J Appl Physiol (1985). 2014 Oct 1;117(7):738-744.

[5] Doscher J. [1998] Accelerometer Design and Applications J Doscher. Analog Devices. https://elpuig.xeill.net/Members/vcarceler/articulos/jugando-con-el-wiimote-y-gnu-linux/sensor971.pdf/at_download/file

[6] Haiying H. [2004] Modeling Inertial Sensors Errors Using Allan Variance H Haiying. University of Calgary URL: https://www.ucalgary.ca/engo_webdocs/NES/04.20201.HaiyingHou.pdf

[7] Yuskel Y. [2008] Notes on Stohastic Errors of Low Cost MEMS Inertial Units. https://pdfs.semanticscholar.org/8099/741b10ce60ff9d370fd7e285899713fcdde6.pdf

[8] Dorofeev NV, Kuzichkin OR. [2010] Problems of multiplicative instability of differential measuring transducers of an electromagnetic field. Questions of Radio Electronics, 1(1):117-122.

[9] Pavlov DV, Petrov MN, Lukin KG. [2013] Development of a dynamic model of a fiber-optic gyroscope. Bulletin of NovSU, 75.

[10] Dyumin AF. [2006] An optimal linear filter in the problem of calibrating errors of inertial angular velocity meters. Fiz.-mat. Sciences, 42.

[11] Bogdanov MB, Saveliev VV. [2012] A method for determining the multiplicative errors of measuring channels of a strap down inertial navigation system containing angular velocity sensors. Technical science, 11-2.

[12] Nikolaevich CI, Ivanovich ND. [2015] Correction of temperature error, approximation of calibration characteristics of sensitive elements of transducer equipment with intrasensory electronics, Measurement, Monitoring Control. The control, 4(14): 1-15.

[13] Tsaplev AV. [2014] The signal conditioning device of the accelerometer sensor of the angle of rotation of the radar antenna devices, AV Tsaplev, NV Dorofeev, OR Kuzichkin.- Radio engineering and telecommunication systems, 4:13-19.

[14] Kuzichkin OR et al. [2008] Methods and devices for transmitting and processing information. Radio engineering, 10: 79-82.

[15] Motorola Electronic Components Datasheet URL: https://datasheetspdf.com/pdf-file/1198249/Motorola/MMA2201D/1

[16] STM microelectronics URL: https://www.st.com/en/mems-and-sensors.html

[17] Accelerometer LIS331DLH. STMicroelectronics. Datasheet. URL: https://www.st.com/resource/en/datasheet/lis331dlh.pdf

[18] Grecheneva AV et al. [2016] Organization of geodynamic monitoring on the basis of the geoelectric method. 4th International Conference: From East Siberia to the Pacific - Geology, Exploration and Development ISBN: 978-946282197-2.

[19] Grecheneva AV et al. [2017] Application of a phase-measuring method in the inclinometric systems of geotechnical monitoring. Proceedings of the 2017 IEEE 9th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2017, 1(3):168-171.

[20] Kuzichkin O, Mikhaleva R, Nikolay V. [2017] Dorofeev Carrying out geodeformation monitoring in karst areas based on accelerometric goniometers. Journal of Fundamental and Applied Sciences, 9(1):1871-1884.

[21] Grecheneva AV et al. [2016] Organization of geodynamic monitoring on the basis of the geoelectric method. 4th International Conference: From East Siberia to the Pacific - Geology, Exploration and Development ISBN: 978-946282197-2.

[22] Kuzichkin O et al. [2017] Regression algorithms eliminate interference with the endogenous character geoecological monitoring of water resources. SGEM, 17(52):749-754, DOI: 10.5593/sgem2017/52/S20.096.

[23] Kuzichkin OR et al. [2017] Design and use of highly sensitive induction sensors for geodynamic monitoring. Journal of Engineering and Applied Sciences. 12(14):3644-3648.

[24] Grecheneva A et al. [2017] The method of selection of the key geodynamic objects. CEUR Workshop Proceedings, 1839:74-83, MIT 2016 Vrnjacka Banja Serbia, 28.08.2016.

[25] Grecheneva A et al. [2017] Positioning of the Goniometric Monitoring System based on the Phase Measuring Principle. International conference on industrial engineering, applications and manufacturing (ICIEAM). Saint Petersburg, ussia, May 16-19, 2017, New York.