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EVALUATION OF ENGINEERING STRUCTURES DEFORMATION (ACCURACY)

(Рекомендовано членами редакційної колегії д-ром геол. наук, проф. О.М. Іванік та д-ром геол. наук, проф. С.А. Вижвою)

The construction of the model of accuracy of the measuring processes of the automated monitoring system of engineering structures deformations from the point of the theory of accuracy is considered in the article. From the point of view of the generalization of the accuracy of measurements by the automated system of engineering structures monitoring, the construction of the model of the measuring process is considered, resulting in separate characteristics and properties of the object to be investigated. In this case these are values of deformations of engineering constructions' structures.

The brief acquaintance with the automated system of monitoring of engineering structures deformations, which represents a chain of optoelectronic devices-deformation marks, which are installed on constructions of structures and fix the created line is given. The use of this system allows to solve the problem of the preventive assessment of the dynamics of local technogenic deformation in the engineering structure and thus to increase the level of technogenic safety of the personnel of the engineering structure.

Compared with modern well-known methods and means for determining the engineering structures deformation, an automated deformation monitoring system has the following advantages:

1. Cross-section geodetic control of deformations (position) of elements of the full volume of engineering structure with increased accuracy.

2. Automated control of engineering structures deformations in real time, including in limited or inaccessible for visual measurements places.

3. Control of the technogenic safety of the engineering structure, prediction of the moment of the emergency, warning about the upcoming critical state (moment) of the engineering structure in real time with the accurate definition of a certain area.

4. Installation of the entire monitoring system occurs during the construction of the structure, pre-installation sites of optoelectronic devices - deformation marks are agreed with the designers and architects.

5. The mean square error of measurement of relative deviations of deformations is not less than 0,1 ÷ 0,5 mm at distances between optoelectronic devices up to 10 m.

6. Information on the magnitude of deviations from the nominal (initial) position goes to the remote central control panel of the system in real time scale.

7. In the case of upcoming moment of dangerous deviation (deformation), the command from the main control panel receives a signal for rapid response with the accurate designation of the place of dangerous deformation.

Keywords: automatic control of deformations of engineering structures, deformation marks, monitoring of deformations of engineering structures.

Formulation of the problem. Modern construction and operation of engineering structures requires the development and dynamic introduction of an automated system for monitoring engineering structures that would measure deformations with increased accuracy and efficiency, would have access to monitoring structures in places not accessible to visual measurements, while all the information about deformation could be promptly received to a remote post for processing.

Analysis of recent research and publications. Modern well-known automated systems of monitoring of engineering structures deformations based on the combined use of modern geodetic instruments such as opto-electronic total stations, GPS and various sensors, etc., have significant disadvantages, which can include both the complexity of the design, and the lack of accuracy of the definition deformations, impossibility to observe the deformations of engineering structures in places unattainable by visual measurements. In addition, these devices and equipment have difficulties in fixing them to structures, high cost and lack of protection from vandalism.

Formulating the goals of the article. The purpose of the article is to construct a model of measuring process carried out by an automated system for monitoring the engineering structures deformation and obtaining values of deformations of engineering constructions' structures.

Presentation of the main research material. The task is solved by creating an automated system for monitoring the deformation of engineering structures. The system consists of a chain of optoelectronic devices - deformation marks, which are installed on the structures of the construction and which fix the generated line.

On fig. 1. There is a block-diagram of created line of automated system of engineering structures monitoring *(Silva el al., 2015; Malik, 2016)* which includes:

1,2, …, n-1, n – optoelectronic (OE) dual-channel devices automated system for monitoring the deformations;

LS1, LS2 – Insignia of the reference geodetic signs of the cavity;

4 – lenses of monitoring system devices;

5 – block of double photovoltaic matrices;

6 – control block;

7 – block of registration, transformation and processing the information;

8 – indication block;

9 – record and information maintenance unit;

10 – block of assessment of the construction structure solidity;

11 – block of subsidence monitoring ΔZ ;

12 – block of monitoring of spatial network deformation $\Delta X, \Delta Y, \Delta Z$;

13 – block of technogenic situation assessment;

14 – signaling and alert block;

15 – means of communication.

Units 7-13 are laptop (or small computer or tablet).

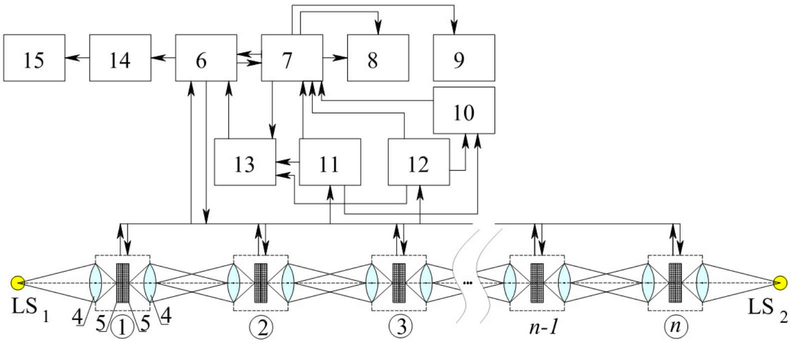

Fig. 1. Block diagram of an established line of automated system of monitoring of engineering structures deformation

The scheme of the most simple OE device – deformation mark (fig. 2), which is included into block-scheme of established automated line from fig. 1, that is blocks 1, 2, …, n contain *(Silva el al., 2015).*

4 – lenses;

matrices

5 – photodetection matrices;

16 – sighting mark in the form of light ring;

17 – light rays from sighting marks 16, which come through lenses 4 and appear on photodetection matrices;

18 – light rays coming from mark 16 into lenses of neighboring devices;

19 – body of OE device;

20 – bases of OE devices bodies;

L-L' – established line.

A prototype of an opto-electronic dual-channel device – a strain mark is shown on fig. 3 *(Malik, 2016).*

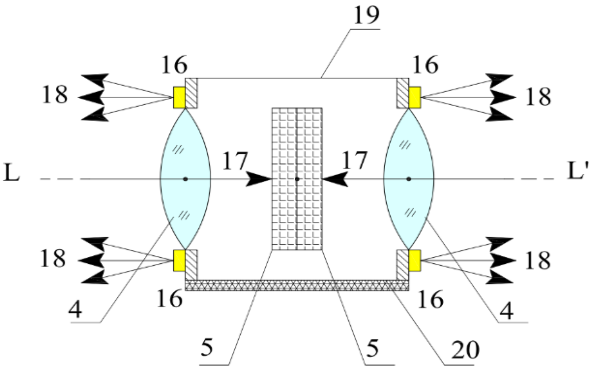

Fig. 2. Scheme of optoelectronic dual channel device-deformation mark

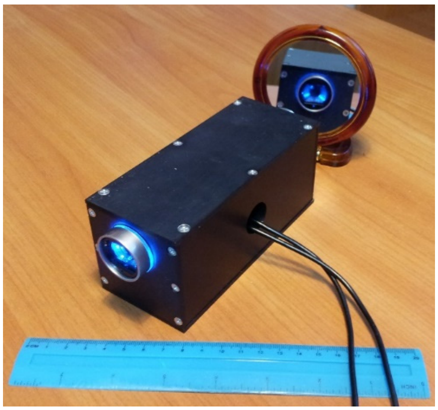

Fig. 3. A prototype of an opto-electronic dual-channel device – deformation mark

To measure the deviations of the optoelectronic device-deformation mark from the cavity it is necessary to measure the magnitude of the linear shift of the beam of light formed by the lens in the working plane of the photomatrix. In this case, the light streams from the visual marks fall on the lenses, which focus images of the marks (light rings around the lenses) on the targets of the photo matrices *(Malik and Bryk, 2016)*.

The automated system for monitoring the deformations of engineering structures includes solving a set of tasks:

1. In-depth geodetic control of deformations (position) of elements of the full volume of structures with increased accuracy.
2. Automated control of deformations of engineering structures in real time, including limited or inaccessible places for visual measurements.
3. Control of technogenic safety of engineering structures, prediction of the moment of emergency, warning about the approach of the critical state (moment) of the engineering structure in real time with the accurate designation of a certain area.

In *(Rosenberg, 1975)* we consider the construction of models of measuring processes and systems from the standpoint of the theory of accuracy. From the point of view of generalization of accuracy of measurements by automated system of monitoring of engineering structures (*Malik 2016).*we consider the construction of the model of the measuring process (as a result of which we obtain certain characteristics and properties of the object of study, in this case - the values of deformations of structures of engineering constructions.

The diagram (fig. 4), which shows the model of the measurement process, is indicated by:

D – a plurality of deformation marks, devices from the automated system of monitoring of engineering structures, fixed on the structures of engineering construction ($d \in D$);

M – mathematical models that describe a plurality of deformation marks ($m \in M$);

E – set of standards of working measures ($e \in E$);

d – deformation mark from the set D ($d \in D$);

IM_d – the main probabilistic mechanism that randomly selects a deformation mark d from a plurality D,

$IM_{\tilde{d}}$ – an accidental mechanism for implementing the measurement process with certain sources of errors;

A_I – an operator that describes an ideal system that is error-free;

ρ – a criterion for evaluating the ideal system A_I;

a_I – a theoretical model of an ideal measurement system that is free of errors;

A – operator of a real system;

a_{t-1} і a_t – the result of a comparison of the ideal and real measurement systems for the previous $t-1$ and current t cycles;

ρ' – a criterion for comparing ideal and real systems;

Z – impact of the environment, man-made factor;

C – technological influence on the system due to errors of assembly technology, errors of nodes and details of devices-deformation marks of the automated system of monitoring of engineering structures ;

σ – random error of determination of coordinates of deformation marks;

Δ – systematic error of determination of coordinates of deformation marks;

$\varepsilon_i = \sigma_i + \Delta_i$ – otal error, consisting of random and systematic $(\varepsilon \in \mathrm{E})$;

$(t-1)$ – previous cycle;

(t) – current cycle;

$\sigma_{\Delta t}$ – random error of the system, or error of measurement of deformation of deformation marks;

$\sigma_{доп}$ – acceptable value of random error;

A_n – operator of control (checking) of the real system;

S – block of storage and accumulation of statistical data;

Φ – filter of deformation results, block of determination of level (degree) of danger;

W – a block of decision making on the possibility of eliminating the causes of deformation of engineering structures;

O3 – block of alert about the rapid approximation of critical deformation and communication.

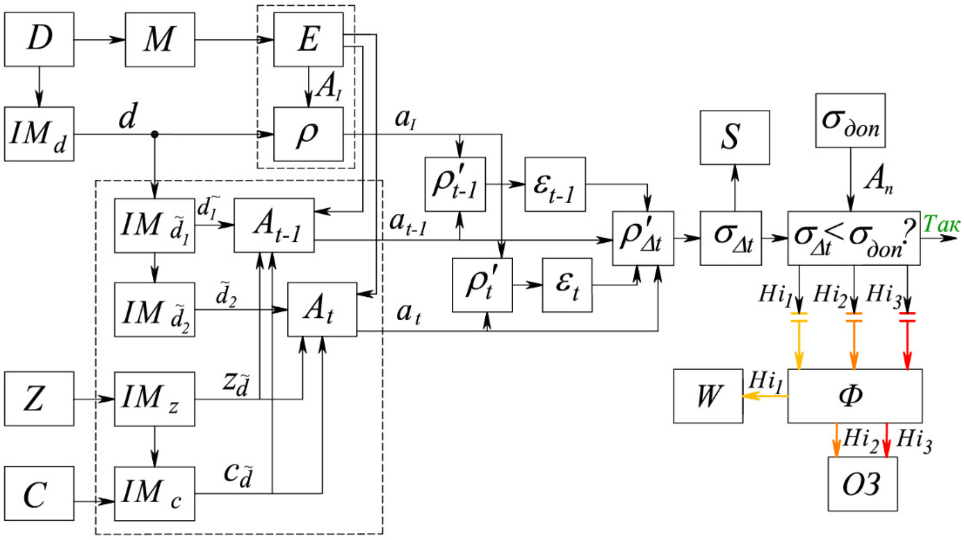

Fig. 4. Model of process of measurement of engineering structures monitoring by automated system

Let us consider the model of the measurement process of engineering structures by an automated monitoring system (fig. 4).

We have a plurality D of deformation marks d fixed on structures of an engineering construction, while $d \in D$, the thesaurus M includes a plurality of mathematical models $m \in M$ that describe a plurality of object-deformation marks included in D. Standards E represent a plurality of standards of working measures, which are set in the form of conditions and requirements for instruments for measuring deformations, norms for the construction of engineering constructions or from the experience of construction and exploitation of engineering structures ($e \in E$) (for example, the requirements for the characteristics of the matrix grid, lens, measuring blocks of optical-electronic automated system for monitoring deformations of engineering structures).

During the observation of engineering structures deformation, the model of the measurement process interacts with one, very specific, deformation mark d from a plurality of deformation marks D, while it is unknown with which of them, but which has changed its original position, which is subject to observation and research as a result. In this case, the choice of mark d is random and can be represented in the form of the action of some probabilistic mechanism IM_d, which randomly selects a certain deformation mark d from a plurality D $(d \in D)$. As a result, it is necessary to identify the deformation of the brand d with one of the standards with a certain value of the parameters, and from there - and with the specific model m^* included in M ($m^* \in M$), closest to d according to the comparison criterion ρ′, which can be represented as:

$$m^* = \arg\min_{m \in M} \rho'(d, m). \tag{1}$$

The ideal system is an ideal construction of an engineering construction with fixed deformation marks on it. The ideal system, which is described by the operator A_I, compares with the help of the operator ρ the deformation mark d with all the standards of the set E, with the result of measuring a_I the deformation of the mark d will be free of errors.

The real system with the operator A_p is a concrete design of the measuring system, which includes different equipment and which is influenced by various factors. In this case, the real system also includes a measure and a comparator, which is described by a model that takes into account the presence of various factors of influence.

The results of measurements are influenced by the factors:

1) the limited number and duration of monitoring data available for monitoring of the process of the deformation marks d, resulting in a specific measurement case model

of the measurement process works with individual implementations $\widetilde{d}_1$, the emergence of which is controlled by a probabilistic mechanism $IM_{\widetilde{d}_1}$ that determines the statistical nature of the measurement problem;

2) the action of the external environment Z, including the man-made factor, which affects the elements of the measuring system and changes in time unpredictably. Realizations $z_{\widetilde{d}}$ are "chosen" by a probabilistic mechanism IM_z;

3) the factor of technological influence C that affects the system due to errors in the assembly of optoelectronic devices, errors in the manufacture of nodes and parts of the automated system of monitoring engineering structures, or as a result of aging and depreciation of the system, is taken into account by the inclusion of the probabilistic mechanism IM_c.

In a real system, the results of measurements are affected by errors that can be interpreted as a result of comparison in accordance with some criterion ρ'_p, which is specified in the normative document or that is put into the system in advance and which depends on the purpose of measurement.

During multiple observations of engineering structures deformations, the parameters a_I of an ideal system remain unchanged, and indicators a_p of the real system change randomly due to the presence of random mechanisms $IM_{\widetilde{d}}$, IM_z, IM_c which are sources of errors.

In the scheme of the model of the process of measurement (fig. 4), a real system of determining the coordinates of deformation marks, at least from two cycles $t-1$ and t respectively. The result of each measurement cycle in the real system changes due to the influence of various factors Z, C, and as a result, each result has a plurality of errors $\varepsilon \in \mathrm{E}$, including random σ and systematic Δ, ($\varepsilon_i = \sigma_i + \Delta_i$), which can be described by the expressions:

$$\varepsilon_{t-1} = \arg\min_{\varepsilon_{t-1}\in \mathrm{E}} \rho'_{t-1}\left(a_I, a_{t-1}\right), \qquad (2)$$

$$\varepsilon_{t} = \arg\min_{\varepsilon_{t}\in \mathrm{E}} \rho'_{t}\left(a_I, a_{t}\right). \qquad (3)$$

According to the fact that the errors obey the normal distribution law, we compare the errors according to a certain criterion $\rho'_{\Delta t}$, taking into account the significance of the systematic error, we introduce an adjustment for its effect, we obtain from the two measurement cycles the amount of errors

$$\sigma_{\Delta t} = \sqrt{\sigma^2_{(t-1)} + \sigma^2_{(t)}}, \qquad (4)$$

which falls into the statistical block where data from all measurement cycles is accumulated. Acceptable level of quality of this system is regulated by the requirements and the value of the admission $\sigma_{доп}$. The control operator A_n carries out a comparison of the error $\sigma_{\Delta t}$ and its permissible value $\sigma_{доп}$ and, based on the results of the processing of the deformation measurements, one assess the situation of the structure of the engineering structure, for example, based on three levels:

Level 1 - is a result close to the lower limit of tolerance, but still within tolerance;

Level 2 – is a result that exceeds the tolerance within certain limits - a signal to the notification block - steps must be taken to strengthen the construction;

Level 3 - is the result of a signal to the block of notification of the need to urgently take measures to evacuate people and values.

The value of the results from all three levels of situation assessment falls into the signaling and notification unit of the automated system of monitoring of engineering structures (block 14, fig. 1). In the case of the danger of the second and third levels, the information comes to the operational response units of the automated system of monitoring of engineering structures (block 15, fig. 1).

The main sources of errors in the automated system for monitoring the deformation of engineering structures one can include the overall mean square error (MSE) of deformation determination by the system, which includes:

Group Z errors – MSE for the influence of the environment, man-made factor;

Group C errors – technological MSE for the impact on the system due to errors in the assembly of devices, errors in the manufacture of nodes and parts of devices-deformation marks of the monitoring system.

Errors of group C: MSE inspection of device-deformation mark system (random); MSE visualization on the center of the light ring of the deformation mark of the device system (random); MSE due to inaccuracy of alignment of the focal length of the device's lens system (random); MSE definition of distances between devices of the system (random); MSE result due to accumulation of errors in the system (random); MSE as a result of instability of foundations (precipitation) under the reference marks (random); MSE information loss in electronic tract (random); MSE transmission of information on the electric channel (random); unpredictable mistakes.

Errors of group Z: MSE due to fluctuations in ambient temperature (random).

In the composition of errors of determination of the coordinates of deformation marks, all the components of the MSE are included, used to determine the deformations by devices of an automated deformation monitoring system.

Conclusions. As a result of construction of the model of the accuracy of the measurement process by automated system of monitoring of deformation of engineering structures we have the following:

1. Theoretical substantiation of the matrix image of the system of deformation measurements of structures of engineering constructions.
2. Recommendations on the choice of optimal control of the process of measuring deformations of engineering structures, which means such control which provides a minimum error in the presence of uncontrolled effects on the deformation of the structure.
3. Mathematical basis for research of an array of deformations of elements of an engineering structure.

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ПОБУДОВА МОДЕЛІ ТОЧНОСТІ АВТОМАТИЗОВАНОЇ СИСТЕМИ МОНІТОРИНГУ ДЕФОРМАЦІЙ ІНЖЕНЕРНИХ СПОРУД

Розглянуто побудову моделі точності вимірювальних процесів автоматизованої системи моніторингу деформацій інженерних споруд з позиції теорії точності. З погляду узагальнення точності вимірювань автоматизованою системою моніторингу інженерних споруд, розглянуто побудову моделі вимірювального процесу, в результаті чого отримано окремі характеристики і властивості об'єкта, що підлягає дослідженню, у даному випадку це величини деформацій конструкцій інженерної споруди. Наведено коротке ознайомлення з автоматизованою системою моніторингу деформацій інженерних споруд, яка являє собою ланцюг оптико-електронних приладів – деформаційних марок, що встановлюються на конструкціях споруди і фіксують створену лінію. Використання даної системи дозволяє вирішити завдання попереджувальної оцінки динаміки локальної техногенної деформації в інженерній споруді і тим самим підвищити рівень техногенної безпеки персоналу інженерної споруди.

Порівняно із сучасними загальновідомими методами і засобами визначення деформацій інженерних споруд, автоматизована система моніторингу деформацій має такі переваги:

1. Наскрізний геодезичний контроль деформацій (положення) елементів повного об'єму інженерної споруди з підвищеною точністю.

2. Автоматизований контроль деформацій інженерних споруд у режимі реального часу, в тому числі в обмежених або недосяжних для візуальних вимірювань місцях.

3. Контроль техногенної безпеки інженерної споруди, передбачення моменту аварійної ситуації, попередження про наближення критично небезпечного стану (моменту) інженерної споруди у реальному масштабі часу з точним позначенням певної ділянки.

4. Монтаж всієї системи моніторингу відбувається під час будівництва споруди, попередньо місця кріплення оптико-електронних приладів – деформаційних марок погоджуються з проектантами і архітекторами.

5. Середньоквадратична похибка вимірювання відносних відхилень деформацій не гірше 0,1 ÷ 0,5 мм при відстанях між оптико-електронними приладами до 10 м.

6. Інформація про величини відхилень від номінального (початкового) положення надходить на віддалений центральний пульт системи у реальному масштабі часу.

7. У випадку наближення моменту небезпечного відхилення (деформації) по команді з головного пульту управління надходить сигнал для швидкого реагування з точним позначенням місця небезпечної деформації.

Ключові слова: автоматичний контроль деформацій інженерних споруд, деформаційні марки, моніторинг деформацій інженерних споруд.

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ПОСТРОЕНИЕ МОДЕЛИ ТОЧНОСТИ АВТОМАТИЗИРОВАННОЙ СИСТЕМЫ МОНИТОРИНГА ДЕФОРМАЦИЙ ИНЖЕНЕРНЫХ СООРУЖЕНИЙ

Рассмотрено построение модели точности измерительных процессов автоматизированной системы мониторинга деформаций инженерных сооружений с позиции теории точности. С точки зрения обобщения точности измерений автоматизированной системой мониторинга инженерных сооружений, рассмотрено построение модели измерительного процесса, в результате чего получены отдельные характеристики и свойства исследуемого объекта, в данном случае это величины деформаций конструкций инженерного сооружения. Автоматизированная система мониторинга деформаций инженерных сооружений представляет собой цепь оптико-электронных приборов – деформационных марок, установленных на конструкциях сооружений и фиксирующих створную линию. Использование данной системы позволяет решить задачу предупреждающей оценки динамики локальной техногенной деформации в инженерном сооружении и, тем самым, повысить уровень техногенной безопасности персонала в инженерном сооружении.

По сравнению с современными общеизвестными методами и средствами определения и измерения деформаций инженерных сооружений, автоматизированная система мониторинга деформаций обладает следующими преимуществами:

1. Сквозной геодезический контроль деформаций (положения) элементов полного объема инженерного сооружения с повышенной точностью.

2. Автоматизированный контроль деформаций инженерных сооружений в режиме реального времени, в том числе в ограниченных или недоступных для визуальных измерений местах.

3. Контроль техногенной безопасности инженерного сооружения, предвидение момента аварийной ситуации, предупреждение про приближение критически опасного момента инженерного сооружения в реальном масштабе времени с точным определением участка.

4. Монтаж всей системы мониторинга происходит во время строительства сооружения, предварительно места закрепления оптико-электронных устройств – деформационных марок утверждаются с проектантами и архитекторами.

5. Среднеквадратическая ошибка измерения относительных отклонений деформаций не превышает 0,1 ÷ 0,5 мм при расстояниях между оптико-электронными устройствами до 10 м.

6. Информация о величинах отклонений от номинального (начального) положения поступает на отдаленный центральных пульт системы в реальном масштабе времени.

7. В случае приближения момента опасного отклонения (деформации) по команде с главного пульта управления поступает сигнал быстрого реагирования с точным уточнением места.

Ключевые слова: автоматический контроль деформаций инженерных сооружений, деформационные марки, мониторинг деформаций инженерных сооружений.