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РАСПОЗНАВАНИЕ КОЛЕС С ПОМОЩЬЮ ЛАЗЕРА ДЛЯ ВЫЧИСЛЕНИЯ ДЕФОРМАЦИИ ШИН

В ходе исследований реализован алгоритм распознавания луча лазера в области колеса транспортного средства, что, несомненно, имеет самостоятельную ценность. Получено минимизированное количество пикселей в ROI (область колеса) для последующего восстановления 3D-модели колес. При такой модели произведены вычисления коэффициентов деформации колес транспортного средства.

Ключевые слова: детектор ребер Канне, дифференциальный оператор Собеля, компьютерное зрение, медианный фильтр, преобразования Хафа.

Lymarenko Yuliia, *PhD, Associate Professor, Department of Computerized System Software, Zaporizhzhya State Engineering Academy, Ukraine, ORCID: http://orcid.org/0000-0002-1643-6939*

Tatievskyi Dmitry, *Postgraduate Student, Department of Computerized System Software, Zaporizhzhya State Engineering Academy, Ukraine, e-mail: dtdissert@gmail.com, ORCID: http://orcid.org/0000-0002-7841-9560*

UDC 539.6
DOI: 10.15587/2312-8372.2018.123463

Gaidaichuk V.,
Kotenko K.,
Kedyk I.

DEVELOPMENT OF THEORETICAL AND EXPERIMENTAL DYNAMIC MONITORING OF LARGE-SCALE BUILDING STRUCTURE

Встановлена доцільність використання динамічного моніторингу в системі контролю технічного стану будівельних споруд. Створена скінченно-елементна модель споруди, обґрунтовано її використання в комплексній системі моніторингу споруди. Розроблено варіант автоматизованої системи експериментального динамічного моніторингу і сформульовані умови ефективного його використання. Розрахунковим способом виявлені моніторингові точки споруди.

Ключові слова: *динамічний моніторинг, частоти і форми власних коливань, скінченно-елементна модель.*

1. Introduction

In recent years there has been a tendency to increase the number of accidents in the construction of industrial and civil infrastructure. So the collapse of the roof underwent the construction of Transvaal-Park in Russia (Moscow, 2004). Similar, the most famous accidents occurred at the exhibition center in the Polish city of Katowice (2006), in the skating rink in Bad Reichel (Germany, 2006), in the shopping center «Maxima» (Riga, Latvia 2013), in a sports complex of a factory of a medical glass in Poltava (Ukraine, 2016).

In most cases, such accidents occur in the winter, are accompanied by human casualties and cause significant economic losses.

In this regard, in order to prevent the emergence of an emergency situation, or localization of its scale, information is needed that reflects the technical condition of the facility in advance and characterizes the trend of its changes. The source of such information can be the results of monitoring performed during the operation of the facility. At the same time, the modern practice of monitoring the technical condition of construction projects indicates the absence of universal methods for monitoring them. Existing monitoring systems do not adequately reflect the actual situation. Influence on the results of control is insufficient account of the structural features of the object, the influence of internal and external factors on it. Informativeness of the monitored indicators and the technical capabilities of existing equipment and so on are inadequate. Therefore, this work provides a solution to the problem of a new method for assessing the technical condition of large-scale building structures and building it on the basis of a monitoring system.

2. The object of research and its technological audit

The object of research is the method of monitoring and assessing the technical condition of the construction of a large-scale building of the International Exhibition Center (Kyiv, Ukraine) on the indicators of its dynamic characteristics.

Provision of trouble-free construction objects requires a systematic control of their technical condition in the process of construction and operation. The engineering and technical support of the buildings carried out for this purpose revealed a number of shortcomings in the existing control systems and made it possible to determine the main directions for the improvement and development of these systems.

The main, until recently, was the use of static deformation parameters of controlled objects: displacements, angles of inclination, rotation, and so on. A typical example of such control is the automated system of static monitoring of the large-scale building structure of the International Exhibition Center, created by SOLDATA [1]. This system provides automated laser monitoring of movements of metal structures at established points. It allows to determine the changes in the absolute values of displacements and, when they reach critical values, timely inform the relevant technical services. But such control characterizes only the local state of the object's constructions. It does not take into account the redistribution of axial forces and moments in individual constructions that occurs in real conditions due to their interaction and other circumstances. It is somewhat arbitrary and the critical value of this indicator is adopted. And the engineering-intuitive definition of observation points brings subjectivity into the control system and can adversely affect the objectivity of its results. In this case, there is a need to search for and use new scientific approaches.

3. The aim and objectives of research

The aim of research is development of a theoretical and experimental dynamic monitoring of a large-scale building structure for assessing its technical condition and the possibility of using the principal provisions of the developed monitoring in control systems of other objects of this class.

To achieve this aim, it is necessary to solve the following tasks:

1. To create a mathematical finite element model of the structure.
2. To verify and adapt the model to the actual operating conditions.
3. To select instrumentation to estimate the frequency and shape of natural oscillations of a building structure.

4. Research of existing solutions of the problem

Analysis of literature data performed at an early stage of the study of this problem shows the promise of using mathematical modeling of controlled building objects and the use of dynamic characteristics of structures in monitoring systems [2]. More recent studies confirm this conclusion [3, 4] and the appropriateness of using natural frequencies, forms of natural oscillations, and the damping decrement of the oscillatory process [5, 6]. Based on the use of these indicators, dynamic monitoring shows high efficiency of its use in control systems of high-rise objects and unique structures [7, 8]. Thanks to the use of dynamic indicators, monitoring allows to characterize the global state of a structure without special observation of its individual elements [8, 9]. There are some examples of the use of this monitoring in relatively simple objects in a constructive way [10]. It seems appropriate to use it in control systems of complex and risky objects. Typical examples of such facilities are large sports arenas, large-scale construction facilities of exhibition centers, industrial infrastructure, etc. Distinguished by the significant structural fullness, different types of structural elements and operational features, such facilities are labor-intensive for mathematical modeling. And the effectiveness of using dynamic indicators to control them requires special research. The fact is that the constructions of this class belong to the category of so-called «flexible». The values of the first three fundamental frequencies of their natural oscillations, in most cases, do not exceed 1 Hz. The wind load on them is significantly different from the impact of high-rise objects. The internal oscillatory process of these objects is inferior to the intensity and contrast indicated. The influence of structural and operational characteristics is more significant.

Information materials that testify to the use of this monitoring to control large-scale building structures in accessible sources are not found.

5. Methods of research

Theoretical and experimental methods are used to achieve this aim. With the help of the first, a mathematical model is constructed for calculating axial forces, bending and twisting moments, knot displacements, stability of structural elements, values of natural frequencies, forms of natural oscillations, determination of monitoring points, and so on. This informativeness is supposed to be used in improving the existing static monitoring of the structure and for assessing its global technical state using dynamic indicators. And the experimental studies provided for supplementing the received information and promptly identifying the initial stage of the threat, to testify the appropriateness and timeliness of introducing changes in the mathematical model.

6. Research results

6.1. Creation of a finite element model of a structure. The general view of the simulated construction of the structure is shown in Fig. 1. To create its mathematical model, software complexes SCAD (Russia) and NASTRAN (USA) are used. The creation procedure include: preprocess preparation, calculation of differential equations, postprocessing and analysis of the results. At the preprocess stage, the geometric characteristics of the cross-section of the structural elements of the structure and the parameters of their physical characteristics are determined and introduced into program complexes (Fig. 2, 3).

The calculated loads are applied (Table 1).

Combinations of loads are applied (Table 2).

The types of finite elements are chosen for use in software complexes. A breakdown of structures into finite elements is carried out in accordance with the finite element mesh of program complexes. Boundary conditions are introduced into the design scheme (joints, couplings) and calculations of differential equations are performed. The obtained results are processed and analyzed at the postprocessing stage and preliminary conclusions are drawn on their basis.

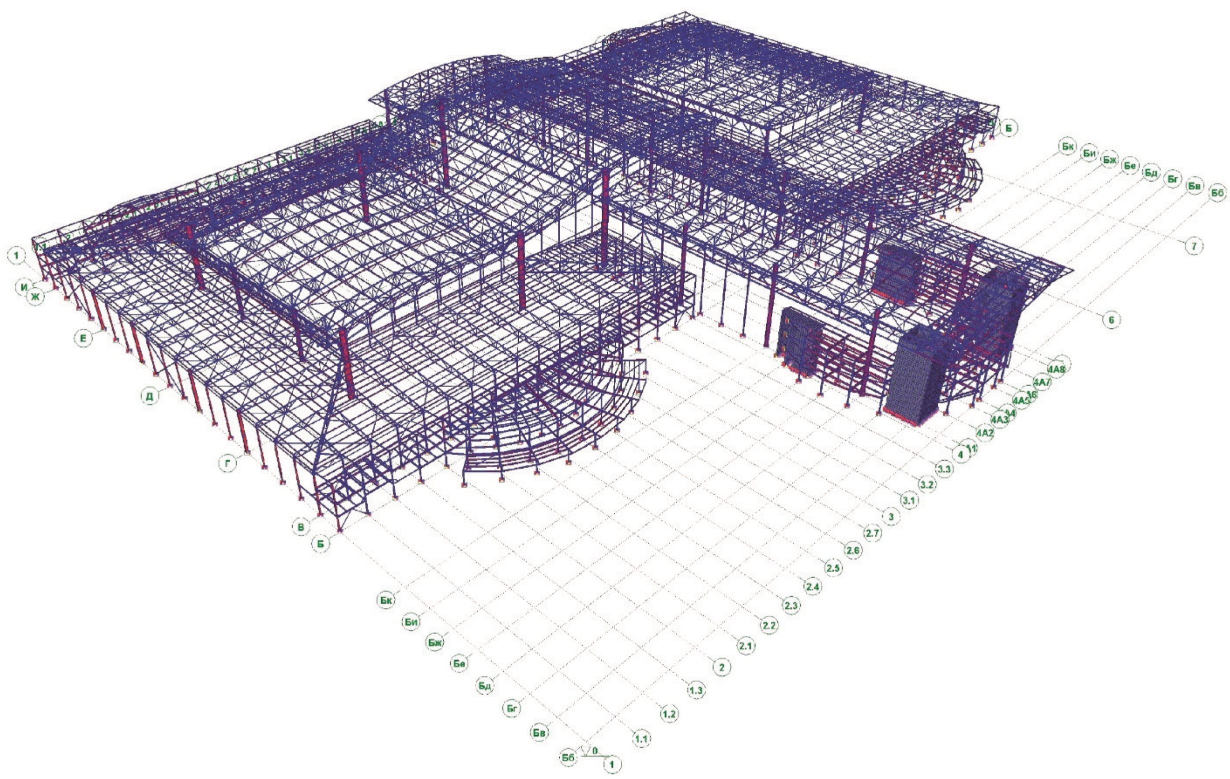

Fig. 1. General construction scheme of the building:
А, Б, Бб…Бк, В…И – alphabetic axes of the structure; 1, 1.1,…1.3, 2, 2.1,…2.7, 3, 3.1,…3.3, 4, 4.А1…4А8, 5…8 – numerical axes of the structure

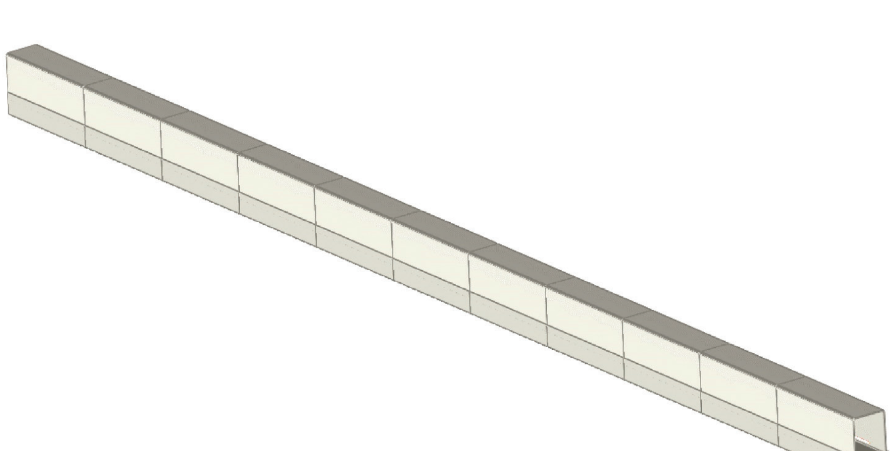

Fig. 2. Elements of the composite section. Pipe 200×160×5 (GOST 30245-94) and a square 200×110×3

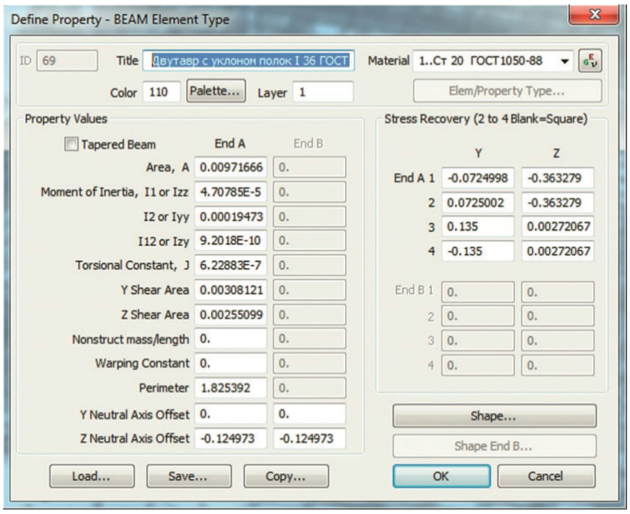

Fig. 3. Characteristics of the composite section. I-beam with a slope of shelves I 36 (GOST 8239-89) and channel 27 У (GOST 8240-97)

Table 1

Load in the finite element model

No.	Load
L1	Own weight
L2	Own weight of enclosing structures
L3	Technological load
L4	Payload
L5	Snow load
L6	Wind load along the *X* axis
L7	Wind load against axis *X*
L8	Wind load along the *Y* axis
L9	Wind load against *Y* axis

Table 2

Combination of loads in the finite element model

No.	Combination of loads
C1	1.0*(L1)+1.0*(L2)+0.95*(L3)+0.9*(L5)+0.9*(L6)
C2	1.0*(L1)+1.0*(L2)+0.95*(L3)+0.9*(L5)+0.9*(L7)
C3	1.0*(L1)+1.0*(L2)+0.95*(L3)+0.9*(L5)+0.9*(L8)
C4	1.0*(L1)+1.0*(L2)+0.95*(L3)+0.9*(L5)+0.9*(L9)
C5	C1*1.25
C6	C2*1.25
C7	C3*1.25
C8	C4*1.25

The main unknowns are: movement and rotation of the nodes of the calculation scheme. The type of the final element is determined:

– geometric form;
– rules that determine the relationship between the movements of nodes of a given element and the nodes of the system;
– physical laws that determine the relationship between internal forces and internal movements;
– set of parameters (stiffness) included in the description of this law.

In this connection, the design is set up in a form suitable for this method (in a set of bodies of the standard type: Beam, Plate) used in international practice [11].

The node in the calculation scheme is represented as an absolutely rigid body of infinitesimal size. Its position in space under deformations of the system is determined by the coordinates of the center and the angle of rotation of the three axes rigidly connected with the node.

The node is represented as an object having six degrees of freedom (three linear displacements and three rotation angles). The system of equations of the displacement method is chosen by superimposing in all nodes of all elms, which prohibited all nodal displacements. The condition of zero effort of these elms is an equilibrium equation, and the displacement of elms is the main unknown of the method. The design scheme is set as a general scheme, that is, deformations and unknowns in the scheme are represented by linear displacements of points along the *X*, *Y*, *Z* directions and rotations in around *RX*, *RY*, *RZ*. The static calculation of the circuit is carried out in a linear form. In the design scheme, generalized elements of the Beam, elements of the Plate type, as well as the Rigid link elements are applied.

For elements of the Beam type, the forces are extracted at the end sections of the elastic part (initial and final), and at the center of the elastic part. The following forces are possible for beam elements:

N – longitudinal force;
MK – the twisting moment;
MY – bending moment with a vector along the *Y* axis;
QZ – transverse force in the direction of the *Z* axis, corresponds to the moment *MY*;
MZ – bending moment with respect to the *Z* axis;
QY – transverse force in the direction of the *Y* axis, corresponds to the moment *MZ*.

Positive directions of effort in the beam elements are adopted as follows:

– for forces *QZ* and *QY* – in the direction of the corresponding axis *Z*, *Y*;
– for the moments *MK*, *MY*, *MZ* – counter-clockwise, if viewed from the end of the corresponding axis *X*, *Y*, *Z*;
– for the longitudinal force *N*, positive values always stretch the beam element.

The total number of finite elements in the model is 107323, and the number of nodes is 97591.

Analysis of the elastic deformation of the structure at each step is realized by solving a system of linearized equations for the finite element model:

$$[K]\{\Delta u\}=\{\Delta f\}-\{r\}, \quad (1)$$

where $[K]$ – the linearized stiffness matrix of the system; $\{\Delta u\}$ – the required vector of growth of displacements; $\{\Delta f\}$ – a vector of increments of given forces; $\{r\}$ – a vector of discrepancies. Due to the fact that for some combination of internal preload forces, the design may lose stability, the buckling of structural elements is investigated on the basis of setting the eigenvalue problem for the linearized system of equations [3–5]:

$$|K+\lambda_i L|=0, \quad (2)$$

where K – stiffness matrix for an unstressed construction; L – stiffness matrix; λ_i – desired eigenvalues of the load

ISSN 2226-3780

parameter (the preload parameter); the straight brackets denote the sign of the determinant calculation.

Frequencies and forms of natural oscillations are determined on the basis of frequency analysis. The equations of motion of structural elements are written in the matrix form:

$$[M]\{\ddot{u}\}+[K]\{u\}=0, \tag{3}$$

where $[K]$ and $[M]$ are the stiffness and mass matrices, respectively, reflecting the elastic and inertial characteristics of the structure; $\{u\}$ – vector of dynamic displacements; dots over the letter denote differentiation with respect to time.

After taking into account the harmonious law of natural oscillations of the structure, the analysis of the system of motion equations (3) reduces to the Sturm-Liouville problem for an algebraic system:

$$\left|K+\lambda_i L\right|\left\{\psi_i\right\}=0, \tag{4}$$

where $\left\{\psi_i\right\}$ – the eigenvector (mode of oscillation), which corresponds to the eigenvalue (circular or cyclic frequency).

In the same way, a finite-element model is created for performing calculations by the SCAD software. The features and requirements of the software package are taken into account. The number of finite elements of the model in SCAD is 29322, and the number of nodes is 18993.

6.2. Verification and validation of the adequacy of the finite element model. The final stage of the research includes the verification of the model created to take into account its effects on the permanent and temporary loads acting on the building structure. Evaluation of the objectivity of calculations and the response of the model to changes in the technical condition of the structure. The inspection includes the identification of the effect of loads on the weight of the enclosing structures and technological equipment. In the NASTRAN software package, these loads are attached to the mass of structures from non-structural mass. In the SCAD complex, this operation is performed through dynamic downloads.

In parallel, the seismic station ZET 048-C, attempted to accelerate vibration of the structure and with their help determined the actual values of the natural frequencies. The results of the calculations and experimental measurements show their convergence (Table 3). Convergence is confirmed by the results of calculations of displacements on both software complexes (Table 4) and the magnitude of axial forces in the elements of the long-span (L=60 m) under-rafter farm ПФ6 [12]. Analysis of 16 of its elements shows a maximum discrepancy of effort (2.33 %) in the central slanting farm and a minimum (0.23 %) in its extreme vertical rack. In this case, the absolute values of the forces calculated by the NASTRAN complex are large compared to their values in SCAD.

Table 3

Natural Oscillation Frequencies

Number of frequency tone	Natural Oscillation Frequencies, Hz		
	Estimated in software systems		Experimental, according to field measurements
	SCAD	NASTRAN	
1	0.506	0.492	0.49–0.51
2	0.556	0.538	0.53–0.57
3	0.660	0.668	0.66–0.69

Table 4

Movement of the nodes by Z, (mm) in models created in SCAD and NASTRAN

Movement of the nodes by Z, (mm) (vertical deflections)			
SCAD		NASTRAN	
min	max	min	max
–37.04	7.59	–34.86	7.48
–127.05	28.57	–133.41	28.32
–174.04	39.24	–187.00	39.86
–174.46	39.39	–187.26	39.92
–182.41	41.14	–193.37	41.26
–182.75	41.22	–193.01	41.19
–217.55	49.05	–233.75	49.83
–218.08	49.24	–234.08	49.90
–228.01	51.42	–241.71	51.57
–228.44	51.53	–241.27	51.49

An influence of the stiffness of the joints of the supporting columns with the foundations, the subsidence of the subsoil under the columns, the appearance of a plastic hinge at the junction of the trusses with the columns are also checked. Such damage is characteristic of real conditions and their appearance in the structure is not excluded, which is analyzed. The obtained results show the effectiveness of the response to them by the model and indicate their danger (Table 5).

The model's response to changes in the technical condition of the structure is estimated by the values of the first three fundamental frequencies of the natural oscillations.

Table 5

The values of the first three natural frequencies

Number of natural frequency	The value of the first three natural frequencies of the structure, Hz				
	Frequency in the normative state of the structure	Frequency in the conditional structural damage			
		The subsidence of the ground under the columns of K1 type		The plastic hinge in the connection of the farm F7 and the column of K2 type	
		frequency value	Deviation from the normative state, %	frequency value	Deviation from the normative state, %
1	0.492	0.474	3.7	0.489	0.6
2	0.538	0.531	1.3	0.531	0.7
3	0.668	0.620	7.8	0.668	0.08

6.3. Examples of practical use of the finite element model. Due to operational specifics, the building structure of the International Exhibition Center in many cases carries negative effects from additional loads of its structures. Such loads arise when using new, unpredictable technological equipment, significant weight of samples of demonstration exhibits, changes in technological processes and so on. Identification of these impacts and assessment of their danger allows the use of the finite element model. With the help of the model, conditions are optimized that guarantee the safety of service personnel and visitors to exhibition exposures.

Positive results are obtained using the finite element model to improve the monitoring system of the structure. With its help, the minimum number of points required to monitor the technical condition of the facility (monitoring points) is established. Their locations on the structures of the building for use in the system of experimental-dynamic monitoring are determined. With the help of the finite element model, it became possible to determine the amplitudes of the oscillations of the structure at different natural frequencies. These studies have made it possible to expand the information capabilities of the modal index. There is a prospect of using the absolute magnitude of its amplitude by analogy with its use for estimating the parameters of forced oscillations that are allowed [13].

Efficiency is also shown in calculations of the directions of vibration at the 3 lowest natural frequencies of the structure (Fig. 4, *a–c*).

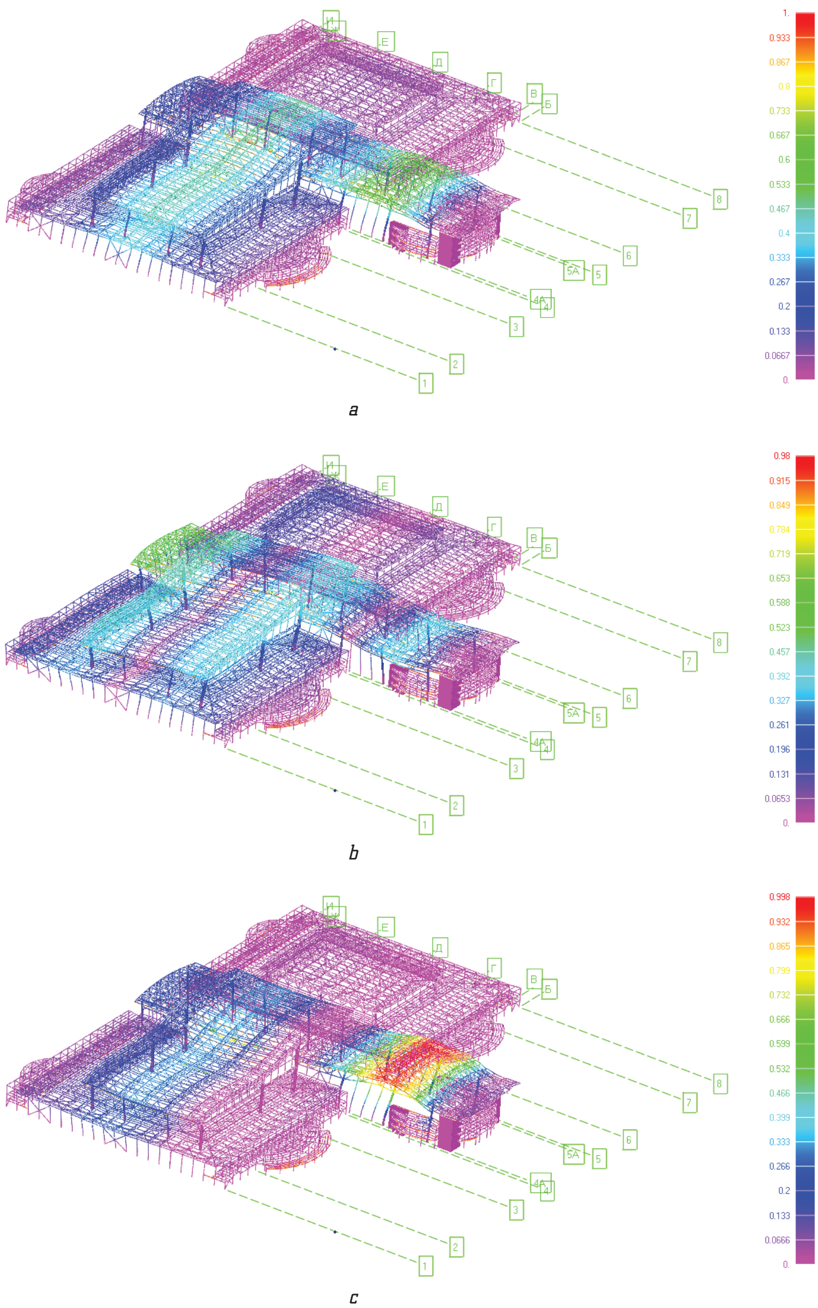

Fig. 4. Forms of natural oscillations of the construction of the International Exhibition Center:
a – the first form of oscillation of the construction of the structure (frequency of oscillations 0.492079 Hz); *b* – the second form of oscillation of the construction of the structure (frequency of oscillations 0.538250 Hz); *c* – the third form of oscillation of the construction of the structure (frequency of oscillations 0.668650 Hz); Б…И – alphabetic axes of the structure; 1...8 – numerical axes of the structure

ISSN 2226-3780

6.4. Experimental monitoring of the building. The proposed variant of the experimental dynamic monitoring of the construction of the International Exhibition Center (Fig. 5) includes the operational and information interfaces. It provides reception of the signals coming from the sensors, their synchronization, registration and transfer to the server, which manages the system with the help of software and operational support. To perform the measurement, the use of three-component accelerometers MS2002+ (Switzerland) is provided. Software and operational support is provided by Geoscop (France) and MS Server (USA) operating system.

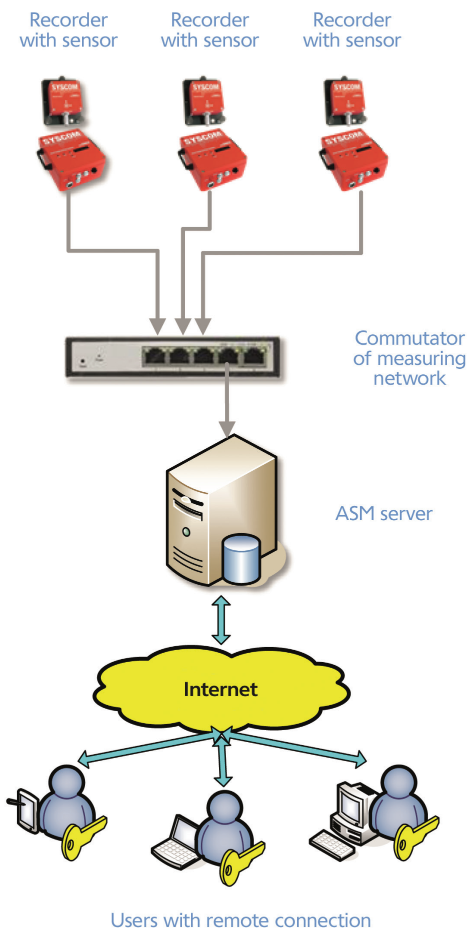

Fig. 5. Structural diagram of the automated monitoring system for dynamic monitoring of the building structure of the International Exhibition Center

When selecting these components, the technical characteristics of the complex and the equipment and the experience of their practical use are taken into consideration. Particular attention is paid to the program complex, which provided:

– simultaneous automatic data collection from sensors and instruments;
– automatic calculation and management of the operational warning system signal criteria;
– visualization and analysis of observational data;
– systematization and automatic printing of reports;
– providing a remote access function for registered customers;
– providing a danger signal when the controlled indicator reaches a critical value.

The monitoring points are determined by calculation using a finite element model of the structure. They are located in the places of maximum movement of the elements of the structure covering on the lower belt of the trusses of the block «B» in the center of the span [14].

To ensure synchronous operation of the measuring stations, it is supposed to use the system controller (synchronizer), which is its controller. The control stations are connected to it according to the «star» scheme. Under such scheme, the signal of the maximum excitation amplitude detected by one of the stations is transmitted to the controller initiating the start of the measurement cycle to other stations.

7. SWOT analysis of research results

Strengths. The research confirms the efficiency of using natural frequencies and the corresponding forms of natural oscillations in the system of assessing the technical state of large-sized building structures, which allow to assess the technical state of the structure, to reveal its changes and to determine their tendency. Based on the use of these indicators, dynamic monitoring allows assessing the global technical condition of the structure and its individual structures, without special monitoring of each of them. A feature of its use in large-sized building structures is the need to protect instrumentation from the impact on it of operational factors of these structures, which «noising» the measurement process.

Effective in the monitoring system of such structures, as well as high-altitude objects [15], is the use of theoretical and experimental methods of monitoring. Particularly effective is their integrated use. Created for this purpose, finite-element models of the structure and a variant of the automated experimental monitoring system make it possible to identify the initial stage of damage to the structure and localize them.

To ensure the adequacy of the model, conventional finite elements and known SCAD and NASTRAN software complexes are used. The creation of two variants of models provided for their mutual control at the stage of practical mastering of the monitoring system and the subsequent use of one of the options in the structure control system, and the other for improving the calculation model itself.

When developing the experimental component of monitoring, modern instrumentation and progressive software and operating software are used, ensuring the objectivity and efficiency of control.

Weaknesses. At the same time, the critical regulatory parameters of the indicators controlled by the rapid identification of places of structural violations and other aspects of the problem remain unidentified. Their solution requires special studies. Landmarks can be the evaluation of the deformed state of structures by the spectrogram [14], ultrasonic testing of connections of structural elements, the use of the navigation field of global satellite systems [16], etc.

Opportunities. The developed method allows to quickly detect changes in the technical state of a controlled structure and is relatively simple and convenient to use. Allows, in spite of the considerable dimensions of the structure, to obtain the necessary information when controlling only a few points of the structure. In this respect it is not very costly. In addition, it allows to control other construction structures of this class, taking into account their design and technological features.

Threats. Negative is the influence of factors causing forced oscillations in the structure. These factors introduce inaccuracies into the process of natural measurements of natural frequencies and introduce changes in the forms of their oscillations.

In international practice, this method is used in monitoring systems for monitoring unique and high-rise structures [7, 10, 16]. Unlike them, the developed method characterizes features of specificity of large-sized structures, their technical condition and less economical.

8. Conclusions

1. Finite-element models of a large-sized building structure are created. The models make it possible to determine the values of the dynamic and static characteristics of the structures and to assess their changes during operation.

2. Verification of the created models is done. It is found that the difference between the calculated and natural values of natural frequencies does not exceed 3 %. Efforts in the elements of the construction of the under-rafter farm by software complexes do not exceed 2.5 %.

3. Monitoring points are defined for the placement of measuring equipment, which are located in the center of the lower belt of farms. Equipment for the monitoring system when performing experimental monitoring of the facility is determined. The use of three-component accelerometers MS2002+, the Geoscop software package and the MS SERVER operating system are provided.

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РАЗРАБОТКА ТЕОРЕТИЧЕСКИ-ЭКСПЕРИМЕНТАЛЬНОГО МОНИТОРИНГА БОЛЬШЕРАЗМЕРНОГО СТРОИТЕЛЬНОГО ЗДАНИЯ

Установлена целесообразность использования динамического мониторинга в системе контроля технического состояния строительных сооружений. Создана конечно-элементная модель сооружения, обоснованно ее использование в комплексной системе мониторинга сооружения. Разработан вариант автоматизированной системы экспериментального динамического мониторинга. Расчетным путем определены мониторинговые точки сооружения.

Ключевые слова: динамический мониторинг, частоты и формы собственных колебаний, конечно-элементная модель.

***Gaidaichuk Viktor,** Doctor of Technical Sciences, Professor, Head of the Department of Theoretical Mechanics, Kyiv National University of Construction and Architecture, Ukraine, e-mail: viktor_gaydaychuk@bigmir.net, ORCID: http://orcid.org/0000-0003-2059-7433*

***Kotenko Konstantin,** Postgraduate Student, Department of Theoretical Mechanics, Kyiv National University of Construction and Architecture, Ukraine, e-mail: box9691@bigmir.net, ORCID: http://orcid.org/0000-0002-3181-3819*

***Kedyk Ihor,** Senior Engineer, SIXENSE Ukraine LLC, Kyiv, Ukraine, e-mail: ihor.kedyk@sixense-group.com, ORCID: http://orcid.org/0000-0003-2775-9191*