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Assessment of building structure using data from dynamic monitoring

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Abstract. The problem on diagnosis and assessment of building constructions on the basis of information of complex dynamic monitoring is considered. Determining factors are divided in accordance with the acting regulatory documents for the diagnostics of structures material properties, the presence of defects in elements and the response parameters of structures subjected to dynamic impact. As a hardware framework for dynamic analysis of the construction response characteristics the 12-channel vibration measuring setup with highly sensitive accelerometers of the seismic range is used. The obtained regularities for changes in the primary factors and their influence on the structure properties are used for the learning of the system for recognition of dynamic signals on the basis of neural networks.

1. Introduction

Current normative documents on health monitoring and estimation of building constructions, scientific research suppose the usage of such informational sources as:

- Data collection from vibrational sensors, placed at critically important points of buildings load-bearing constructions.
- From signal sensors for monitoring of cracks disclosure.
- Geotechnical monitoring sensors.
- Additional instrumental tools of watching for deformations and displacements of load-bearing constructions and soil.
- Visual monitoring.

The data received is quite diverse and has to be the source for evaluation of integral characteristics and indicators of changes in load-bearing structures of building objects. However, it should be mentioned, there is a lack of effective methodologies on description of measured parameters and processing methods for estimation of building constructions states. As a result, there could be formulated following tasks, required for the effective development and realization of monitoring systems for building constructions:

- The development of optimal criteria for result measurement estimations of dynamic, deformational and strength characteristics for the problem of object state analysis.

- The development of methodic for evaluation of criterial indicators of the assessment, including in real time.
- The software and hardware complexes development of the SMIC destination in the framework of practical implementation of the developed criteria and methods for assessing the state of the object construction in accordance with GOST R 22.1.12-2005.
- Complex risk assessment and forecasting of load-bearing capacity of the construction object, including cases of natural or man-made emergency situations.

There could be described numerous approaches to solve the problem stated, including differences in eigen frequencies of damaged buildings. Firs articles in this field could be dated by beginning of 90s, such as the study of cable truss bridges [1]. However, the overwhelming majority of authors describe a low sensitivity of these methods to the damage, in other words with great damage rate of constructions the changings in eigen frequencies is relatively small. The overview of results is published, for example, in [2].

Another approach is study of eigen vibration shapes – the group of MAC methods (Modal Assurance Criterion). This criterion demonstrates good results, but there exists a practical complexity in a correct model development for complex buildings as well as recognition of eigen vibration shapes using signals detected. This problem could be partially solved by the installation on the buildings surface of vibrational sensors with stated characteristics.

Last years, due to improved calculation abilities and machine learning, the new wave of interest has born to exploit neural network methods in terms of non-destructive testing. This could be found in following articles [3-5]. The information on usage of machine learning algorithms in the field of structural health-monitoring for buildings is described in [6-8].

One of the vital problems being discussed while studying methods for buildings health monitoring using changings in corresponding dynamic characteristics is an ambiguity, rising due to the fact, that the signals registered contain the construction response as well as external effects characteristics. Thus, most of the studies are concentrated about the system protection against any fake reactions from external effects characteristics and at the same time not to lose the true signals changings, caused by construction deformation [9-10].

2. Problem statement

Consider the process of assessing the state of a building object on a finite set $S = (s_i), \quad i = 1,2,...,N$ based on the results of dynamic measurements for corresponding characteristics over a time interval $t \in [0,T]$ and the study of equations of state

$$\mathbf{y}(t) = \mathbf{F}\left(\mathbf{x}(t), \mathbf{v}(t), \mathbf{p}, \mathbf{r}^{(i)}(t), \mathbf{r}^{(e)}(t)\right),$$

here: $\mathbf{x}(t)$ - vector of external influences on the object from the environment side;
$\mathbf{y}(t)$ - vector of measured characteristics;
$\mathbf{v}(t)$ - vector of controlled impacts on the monitoring object;
$\mathbf{p}$ - vector of geometric and physical design parameters;
$\mathbf{r}^{(i)}(t)$ - vector of structural elements internal connections;
$\mathbf{r}^{(e)}(t)$ - vector of object relations with the external environment.

The complexity of the problem for the state diagnostics of a building object using dynamic monitoring data is determined by the factors:

- lack of strict criteria for assessment of the state s_i with a description of its compliance with the range of measured characteristics $\mathbf{y}(t)$;
- most often the lack of accurate information about the initial state and dynamic properties of the structure in the absence of damage and defects;
- random nature of the dynamic impact of a complex spectral composition on the object from the environment $\mathbf{X}(\omega) = \int_{-\infty}^{+\infty} \mathbf{x}(t) \exp(i\omega t)dt$;
- a significant influence of the external links of the building object with the environment: a ground foundation with complex dispersion properties $\mathbf{R}^{(e)}(\omega)$;
- a high degree of indeterminacy in the behavior of the construction modeled due to the unclear specification of physical parameters and relationships.

3. Solution

To solve the problem effectively, it is necessary to rely on information about the object obtained for some time, temporal character, using the entire history of observations to analyze the current state of the object. In addition, the assessment is subject not only to changes in the dynamic characteristics of the object, but also its internal properties of physical and geometric nature $\mathbf{p}$.

In order to determine the function of state $\mathbf{F}$ it is proposed to use the methods of finite and boundary elements to describe the stress-strain state of the object construction placed on the surface of multilayered substrate in the steady-state mode with frequency ω.

Using one of the variants of discrete harmonic analysis [11], separating the effects on external and controllable, we have

$$\mathbf{y}(t) = \sum_{\kappa} \left(\mathbf{X}(\omega_k)\mathbf{F}_x\left(\mathbf{p}, \mathbf{R}^{(i)}(\omega_k), \mathbf{R}^{(e)}(\omega_k)\right) + \mathbf{V}(\omega_k)\mathbf{F}_u\left(\mathbf{p}, \mathbf{R}^{(i)}(\omega_k)\right)\right) \exp[-i\omega_k t] \quad (1)$$

The general formulation of the harmonic problem can be reduced to a conjoint solution of the linear algebraic equations system, which follows from the equations of motion of a surface object with allowance for a buried foundation of the form:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \boldsymbol{\tau},$$

where $\mathbf{M}, \mathbf{C}, \mathbf{K}$ - mass matrix, resistance and rigidity of the structure,

$\mathbf{u}$ - vector of nodal displacements,

$\boldsymbol{\tau}$ - nodal force vector.

As well as boundary integral equations

$$\frac{1}{2}\mathbf{u}^{(\gamma)}(\mathbf{r}_0) + \int_{\gamma} \mathbf{T}^*(\mathbf{r}_0, \mathbf{r}, \omega) \cdot \mathbf{n}(\mathbf{r}) \cdot \mathbf{u}^{(\gamma)}(\mathbf{r})ds = \int_{\gamma} \mathbf{U}^*(\mathbf{r}_0, \mathbf{r}, \omega) \cdot \boldsymbol{\tau}^{(\gamma)}(\mathbf{r})ds$$

relative to the same values at the interface of the foundation and the multilayered base (figure 1.).

$\mathbf{T}^*(\mathbf{r}_0, \mathbf{r}, \omega)$, $\mathbf{U}^*(\mathbf{r}_0, \mathbf{r}, \omega)$ - matrices of fundamental solutions for a multilayer half-space, realized with the superposition principle [12]. The properties of these matrices directly determine the characteristics of the object's relationships with the external environment $\mathbf{R}^{(e)}(\omega)$.

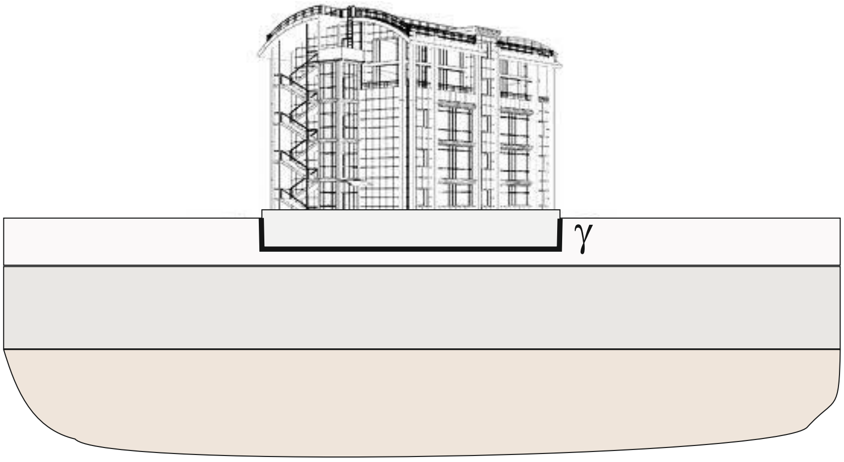

Figure 1. Object on the layered foundation

The next task for the development of an object monitoring system is to identify the diagnostic features that are most sensitive to changing of the object properties and its relationships, based on the equation of state (1).In the time domain, in this study, the maximum values of the displacement amplitudes in a given set of observation points are singled out and the energy of oscillations scattered by the structure in the active impact region of the form $\mathbf{v}(t)$. In the frequency domain, the analysis of natural vibration modes, damping decrements, the distribution of vibration energy over specified frequency ranges, and the amplitude- and phase-frequency characteristics of the response of structural elements are most often used.

We will assume that some diagnostic feature d is a functional of the vector of measured characteristics $\mathbf{y}(t)$:

$$d = \Phi(\mathbf{y}(t)).$$

Let $\delta d = d(\tau_i) - d(\tau_{i-1})$ - the temporal variation of this characteristic associated with consecutive moments τ_i of the experiment evaluation to register the feature. Then, with small changes in the properties of the object and its relationships, we can assume that

$$\delta d \approx \frac{\partial \Phi}{\partial y} \sum_{\kappa} \begin{pmatrix} \mathbf{X}(\omega_k)\left[\frac{\partial \mathbf{F}_x}{\partial \mathbf{p}}\delta\mathbf{p} + \frac{\partial \mathbf{F}_x}{\partial \mathbf{R}^{(i)}}\delta\mathbf{R}^{(i)} + \frac{\partial \mathbf{F}_x}{\partial \mathbf{R}^{(e)}}\delta\mathbf{R}^{(e)}\right] + \\ + \mathbf{V}(\omega_k)\left[\frac{\partial \mathbf{F}_v}{\partial \mathbf{p}}\delta\mathbf{p} + \frac{\partial \mathbf{F}_v}{\partial \mathbf{R}^{(i)}}\delta\mathbf{R}^{(i)}\right] \end{pmatrix} \exp[-i\omega_k t] \quad (2).$$

Expression (2) allows due to the analysis of the coefficients of influence $\frac{\partial \mathbf{F}_x}{\partial \mathbf{p}}$, $\frac{\partial \mathbf{F}_x}{\partial \mathbf{R}^{(i)}}$, … using the object model on the basis of the methods of finite and boundary elements:

- to divide the action of external and internal influence factors on the construction, first of all, the differences in the spectral composition of these influences $\mathbf{X}(\omega_k)$, $\mathbf{V}(\omega_k)$;
- to identify the most important frequency ranges of the measured characteristics;
- to prepare a base of standards for solving the problem of inverse calculation on determination of the change in properties of the structure based on the results of dynamic monitoring.

4. Practical case

As an example, we present an analysis of the simplest object on the surface of a multilayer foundation - non-rigid pavement using the FWD method.

Figure 2. Non-rigid pavement on the multilayered ground

Here, the criteria of the pavement quality is the calculation of the elastic deflection, which determines the required level of the general elasticity modulus on the surface of the structure, taking into account the soil foundation. For its application, it suffices to estimate the vector of the design parameters $\mathbf{p} = \{E_1, E_2, ..., E_n\}$ consisting of elasticity modules for structural layers. As the vector of the measured characteristics the vertical movements are used of the pavement surface in a number of fixed observation points $r_j, j = 1,...,m$. The hardware base for analyzing the dynamic response characteristics of the structure is a 12-channel vibration measuring complex with highly sensitive accelerometers of the seismic range. The movements values are determined by the integration and filtration procedures from the sensors:

$$\mathbf{y}(t) = \{U_z(r_1, t), ..., U_z(r_m, t)\}.$$

As diagnostic feature there is selected the form of dependence for the detected signal maximum value on the time from distance r_j to the source of excitation

$$\mathbf{d} = \max_t \mathbf{y}(t).$$

With the use of the mathematical model constructed and analysis of the influence coefficients according to the equation 2, some optimal conditions for carrying out the experiment are determined In particular, the duration $\tau = 0.003c$ of the impulse impact on the construction, determining the spectral composition of the response, and the location of sensors on the surface (figure 3.).

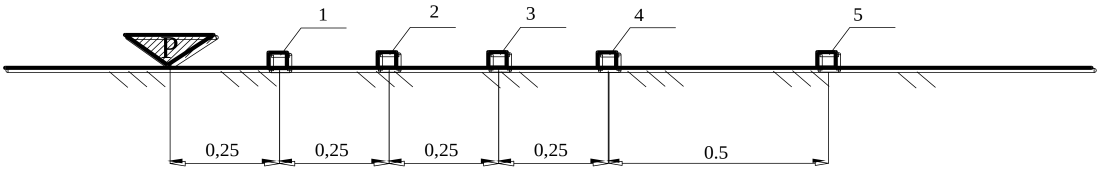

Figure 3. Sensors location on the surface

On the figure 4 the dependence of the maximum vertical displacements on the surface at 5 observation points with linear approximation at intermediate points is shown.

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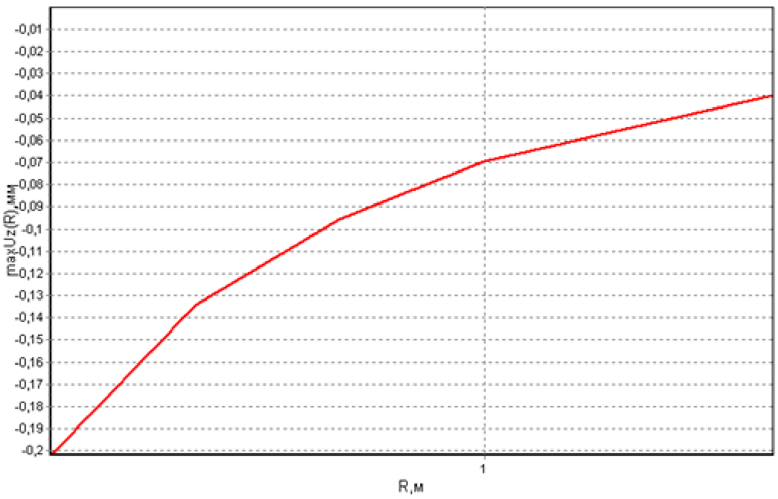

Figure 4. Maximal vertical displacements for 5 viewpoints

To determine the moduli of elasticity for constructive layers, the least squares method is used with minimization of the smoothing error functional:

$$G(E_i) = \sum_{j=1}^{m} \left(U_z(r_j, E_i) - d_j\right)^2 + \lambda \sum_{k=1}^{n} \left(E_k - E_k^{(0)}\right)^2 ,$$

Here: $U_z(r_j, E_i)$ - the calculated values of the maximum displacements on the medium surface from the model,

d_j - experimental data,

$E_k^{(0)}$ - elasticity parameters for layers, determined during the initial design of structure.

The regularization parameter λ is determined on the basis of the generalized discrepancy principle [13]:

$$\sum_{j=1}^{m} \left(U_z(r_j, E_i) - d_j\right)^2 - \left(\delta + \lambda \sum_{k=1}^{n} \left(E_k - E_k^{(0)}\right)^2\right)^2 - \mu^2 = 0,$$

where δ - measurement error; $\mu = \max_{j} \inf_{E} \left|U_x(r_j, E_i) - d_j\right|$ - measure of model and approximate measurements incompatibility.

The results given in the example demonstrated a good reconstruction of the elastic parameters for the structural layers and allowed to estimate the current state of the construction. However, for better account of the construction behavior while changing external conditions and estimating the remaining resource, it is necessary to accumulate the obtained diagnostic information.

5. Discussion

When solving the tasks formulated, an important element is the development of structures for the information integrated accounting, aggregation and application to the creation of information and diagnostic systems, taking into account the accumulation of information. One of such development tool can be neural networks using smart sensors.

The proposed approach is based on the synthesis of an intelligent monitoring system with a three-level hierarchical structure: the lower level is based on the information collection subsystem, including the usage of sensor networks that monitor the basic parameters of objects; the middle level is the system of information aggregation and clustering using neural networks with the large volume of input information; the top level is made up of algorithms for intellectual support for the making of diagnostic solutions and the development on their basis user interfaces to cooperate with the system.

At the lower level, intelligent sensor devices are relatively independent elements that have rules for processing input information. In particular, they use procedures for window and frequency data filtering, averaging, etc. with the focus on the use of information as inputs to the neural network at the average level. For the elements of information visual, for example crack disclosure, the state of structural elements, the regulated measurement scales are used. Thus, the structure of information flows for the neural network has heterogeneity both in origin, composition, and temporal characteristics (static, dynamic).The information aggregation task is performed by the interaction of the central focal point detection system and feedback system of neural mid-level network.

The structure of the middle level neural network is focused on the learning without a teacher in the presence of a large number of training samples. The objective of the network is to identify the internal patterns of information distribution and to select the most significant features determined by the network outputs for their further use in the top-level diagnostic subsystem.

The solution of the problem for final diagnostics of the construction state is carried out by a multilayer neural network, matched by outputs and inputs with the middle level neural network. For the corresponding training, the expert standards are used, using existing normative assessments and involving mathematical models of building structures behavior at various states, as described above, as well as methods for identifying defects in structures [14].

6. Conclusion

Consequently, there proposed an approach for the assessment of buildings state on the basis of complex integrated monitoring information, obtained via sensors, detection of dependencies between the sensor data and the object properties with mathematical modeling and the development of state recognition neural network.

Acknowledgments

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