Automated monitoring systems for defects and damages of building structures and materials

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Abstract. The automated systems for monitoring defects and damages of building structures and materials are considered. The presented systems make it possible to obtain information on the building structures cracks and joints' opening, the measurements of oscillation and shock acceleration, dynamic soil testing and defects control in composite materials. The "System for monitoring the state of cracks and joints of buildings and structures" is one of the presented systems. This system is necessary for collecting and transmitting information about the cracks and joints' opening width of the building structures as well as environmental conditions, can be used when inspecting buildings and structures, as well as in automated systems for monitoring the buildings and structures' technical condition. The modernization of the system sensor makes it possible to measure the humidity and temperature of the external environment and to determine the dependence of the crack opening width on weather conditions. The next element presented by the system is a sensor for measuring oscillation and shock acceleration, also based on an electrochemical principle of operation. The invention makes it possible to solve the problems of increasing the reliability of converting dynamic mechanical quantities into an electrical signal in a wide range of loads and frequencies. It can be used on the construction sites, for seismic measurements and experimental studies. Further, in the system under consideration, an element of which is a load cell sensor, designed to measure voltage in foundation soils, based on an electrochemical principle of action. Load cell allows performing dynamic soil tests, while the technical result is achieved in increasing the device reliability and the measurements accuracy. To determine the defects of composite materials, a non-destructive testing system based on the acoustic emission signals analysis is considered.

Introduction
A change in the performance characteristics and a decrease in the construction operational properties of buildings and structures occurs as a result of exposure to aggressive technological and natural influences. In addition, such negative phenomena are promoted by errors in design, damage due to violation of manufacturing and installation technologies, defects due to improper operation and untimely repairs, metal corrosion, biochemical effects, materials aging [1-5]. There are different types of composite materials, which differ in their composition and properties. The most widespread and used in construction are, for example, such types as sandwich panels, carbon fiber panels, laminated materials,
textolites, fiberglass, which have high performance and decorative effect. Composite is used not only in the construction of residential buildings. It is difficult to imagine a bridge or dam that does not use CFRP panels. Various architectural elements, such as arches or domes, are also often created using composite materials. This is beneficial for the developers, since it provides them with significant savings in the construction of structures, installation, storage and transportation of material, and at the same time, the reliability, quality and other operational characteristics of the future building are not affected. Non-destructive products’ testing is a necessary means of improving the quality of products made from composite materials. Of particular importance is the control of products operating in corrosive environments, experiencing high thermal stresses, oscillation loads, etc. Composite materials for a number of properties associated with the penetrating radiation propagation occupy an intermediate position between metals and concretes, for which non-destructive testing methods and industrial equipment for testing by these methods have been developed. Analysis and systematization of the current and periodic inspections’ results, as well as the results of special instrumental examinations of industrial buildings, make it possible to analyze the change in the damage size to building structures in time, to identify the work dynamics of the structures, to calculate the residual life of an industrial building and to take timely measures to prevent its destruction. ... The development of devices and sensors for instrumental measurements of static deformations and stresses has been carried out in Platov South-Russian State Polytechnic University (NPI) for several decades [6 - 8]. The proposed work continues the study of static deformations and dynamic stresses on the same methodological principles.

**Materials and methods**

One of the first monitoring systems under consideration, consisting of one or more displacement sensors and a recording device, for example a computer or laptop, allows the crack opening width measurements of buildings and structures. The automated process of transmitting data via wireless communication is especially relevant if the controlled cracks are located in hard-to-reach places [9, 10].

Each displacement sensor (Fig. 1) consists of: a slide-wire and a current collector, an analog-to-digital converter, a microcontroller, a transmitting radio module with Zigbee protocol support, a chemical supply voltage source and a clock-alarm module.

The operation of the sensor is that when the controlled crack expands, the distance between the sensor body and the stop for the retractable spring-loaded dial indicator rod is increased, which shows the movement. For visual monitoring of the system, standard hour-type indicators are used, configured for the frequency of signal removal 1-2 times a day, followed by the sensor transition to sleep mode, which leads to significant energy savings. The slide-wire current collector is mechanically connected to the moving dial indicator rod, it receives a signal proportional to the sliding rod movement. Further, the signal from the current collector goes to the analog-to-digital converter, where the input analog signal is converted into a digital code and enters the microcontroller input and through the transmitting radio module transmits the displacement value to the receiving radio module and the recording device. In this regard, there is no need to use wired communication lines. If it becomes necessary to monitor several cracks located in different parts of the building at the same time, several sensors are used according to the number of cracks being controlled. Further, the receiving radio module alternately communicates with the transmitting radio modules that are part of each sensor. Each of them has its own number and transmits information over the radio channel to the recording device.

In the process of work, a second-generation sensor was developed, which includes additional means of measuring a temperature and humidity sensor, which makes it possible to expand the device functionality by increasing the number of determined parameters and to increase monitoring efficiency. The results obtained at the facility are automatically defined in the database for further analysis.

A sensor for measuring mechanical quantities is an element of a system that uses an electrochemical operation principle. The monitoring system is designed to convert dynamic mechanical quantities, including oscillation and shock acceleration, into an electrical signal and can be used in various industries, in particular in the construction field, for seismic measurements and experimental research. The mechanical value sensor consists of a support made of an electrically insulating material, an elastic
conductive plate and an inertial element, two electrochemical cells, each of which includes a housing, an electrolyte, and a current-collecting counter electrode. When the sensor is exposed to oscillation, seismic oscillations and other shocks, they are perceived by an elastic metal plate with an inertial element, while the upper and lower surfaces of the metal plate are alternately stretched and compressed. Since the change in the area of the cells’ deformable electrodes is close in magnitude, but opposite in sign, the output signal is doubled. Thus, the mechanical deformation direct transformation effect of the sensitive elastic element into an electrical signal is achieved. One of the advantages of sensors based on the "solid metal electrode interfacial layer elastic charging effect" is the direct transformation of an elastic element deformation (electrode of an electrochemical cell) into an electrical signal, which increases the reliability of the measurements under dynamic loads that change rapidly over time.

The next sensor is the load cell for measuring stress in soils. The invention relates to a measuring technique and is intended to measure the stress in soils under dynamic loads, in particular, during soil compaction, blasting, earthquake and can be used in construction, mining, experimental research [11]. The load cell works as follows (Figure 1). When dynamic stresses arise in soils, they are perceived by the elastic membrane of the working cover, while the hydraulic fluid deforms the elastic metal membrane, and the liquid electrolyte deforms the elastic metal membrane of the electrochemical cell [12].

**Figure 1.** Constructive diagram of the electrochemical load cell: 1 - annular body and working cover; 2 - two round elastic membranes

Under elastic tension-compression of a flat plate, its initial area changes linearly. In the case of a circular membrane clamped along the contour, the design scheme is shown in Figure 2. It can be seen that in the area of the circular ring and the central part of the membrane, the same in magnitude, but opposite in sign deformations occur. When such a membrane contacts electrolyte, the electrode potential will not change during its deformation. In the proposed device, the use of an elastic electrically insulating protective coating in the form of a circular ring with an inner radius equal to half the electrode membrane radius makes it possible to select the central part of the membrane-electrodes, one of which will experience tension and the other compression and, therefore, the appearance of an electrical signal between them.
Figure 2. Design model, rigidly embedded along the contour of the membrane under load

The carried-out tests of the load cell showed its stability under shock loads.

The specific properties of composite materials require the development of non-standard methods and means of non-destructive testing. One of such methods is acoustic spectral-timbre non-destructive testing of products. On its basis, the authors have developed a stand for non-destructive testing of composite materials, the block diagram of which is shown in (Figure 3).

![Figure 3](image)

Figure 3. Block diagram of the stand for spectral-timbre non-destructive testing of composite materials.
1 - generator of electrical oscillations; 2 - frequency counter; 3 - computer; 4 - amplifier; 5 - piezoceramic sensor; 6 - tested item; 7 - supports; 8 - sensor generator.

In the acoustic method, the emitting and receiving piezoelectric sensors are placed on different sides of the sample. A defect located in the ultrasonic signal propagation path reduces the signal energy transmitted from the transmitter to the receiver due to the waves’ scattering in different directions. This happens when the acoustic wave impedances the material and the defective medium differ significantly. Therefore, it is most effective to detect the defects in the form of widespread air inclusions, single large cracks, systems of small cracks, cavities, delamination, etc. In the presence of such a defect, the signal level reaching the receiving sensor and recorded by a computer turns out to be significantly lower than the signal level in places without defects.

The discussion of the results
Considering the system, the element of which is a load cell sensor, we note the difference from analogues, which consists in the use of an electrochemical principle for the action.
When a metal electrode contacts an electrolyte solution at the metal-liquid interface, a potential shock $\phi$ is considered in electrochemistry to occur based on electrical double layer (edl). In the field of concentrated electrolyte solutions edl likened to a flat capacitor, one of the plates of which is formed by charges of a flat metal electrode $q$ on the surface, and the other - by the charges of the opposite sign ions, adjacent from the solution to the electrode surface at a distance $d$, equal to the ion radius. The charge density will be proportional to the potential jump between the metal and the solution, and is determined by the ratio

$$ q = \phi \cdot c $$

where $c$ – is edl capacity.

The capacity of a flat condenser is found by the formula

$$ c = \varepsilon \cdot S / 4\pi d $$

where in the case under consideration $S$ – is the surface area size of the electrode in contact with the electrolyte; $\varepsilon$ – is a dielectric solvent constant.

The work of the load cell was based on the "effect of elastic charging of the interfacial layer of a solid metal electrode" [12].

The essence of this effect lies in the fact that the surface of a metal electrode in contact with an electrolyte increases or decreases by elastic deformation. In this case, according to (2), the edl capacity and if the electrode charge is maintained constant, for example, by introducing a damping resistance into the electrode circuit, then according to (1) the potential of the electrode itself is relative to the solution changes, which is more convenient for recording. The resistance is chosen so high that the interfacial layer does not have time to discharge during the deformation period (the discharge time constant is equal to the electrode capacity product by the indicated resistance). Analyzing the system for determining defects in composite materials using emitting and receiving piezoelectric sensors, the acoustic method is used. In this case, the fast Fourier transform method (FTM) can be used to analyze the acoustic emission signals generated by the formed defects. In this case, the transition from physical parameters to the frequency-amplitude energy spectrum parameters obtained from the time series of samples, the signal, by the discrete fast Fourier transform is carried out. Non-standard means of assessing the products quality, technology of its production using the analysis of acoustic emission (AE) signals arising from the diagnosed systems’ generator. Decomposition of these signals into natural elementary components of the Fourier spectrum, based on higher timbre harmonics, makes it possible to identify the AE sources and evaluate their role in the product quality analysis. Let the acoustic emission signal be sampled in time in some way. Then the samples for $N$ signal can be written (3) its following representation in the frequency domain:

$$ X(k) = \frac{1}{N} \sum_{n=1}^{N-1} x(n) \left[ \cos \frac{2\pi nk}{N} - j\sin \frac{2\pi nk}{N} \right], \quad 0 \leq k \leq N - 1 $$

where $n$ – denotes the sampling indices (discrete) of the signal in the time domain,

$k$ – denotes the sampling indices (discrete) of the signal in the frequency domain,

$x(n)$ - denotes the sampling indices (discrete) of the signal in the frequency domain,

$X(k)$ - denotes the frequency domain samples.

Signal amplitudes $X(k)$ can be calculated in accordance with the following relations (4):
\[
\begin{align*}
A(X(k)) &= \sqrt{\text{Re}(X(k))^2 + \text{Im}(X(k))^2} \quad \text{--- indication amplitude } X(k), \\
\text{Re}(X(k)) &= \frac{2}{N} \sum_{n=0}^{N-1} x(n) \cos\left(\frac{2\pi nk}{N}\right) \quad \text{--- FTM real part}, \\
\text{Im}(X(k)) &= -\frac{2}{N} \sum_{n=0}^{N-1} x(n) \sin\left(\frac{2\pi nk}{N}\right) \quad \text{--- FTM virtual part}.
\end{align*}
\]

(4)

To assess a defect in a particular sample, it is possible to use the method of studying the set of modal harmonics based on the FTM method [13]. In accordance with this method, a database containing information on subsets of modal harmonics corresponding to a particular defect in the sample under study is preliminarily formed. Subsequently, many harmonics of the Fourier spectrum of the acoustic emission signal of the sample are analyzed in real time, and modal harmonics corresponding to one or another defect are distinguished in it. The presence of these modal harmonics indicates the presence of a defect in the sample, data about which are stored in the computer database. To assess the shape and size of a defect contained in a test sample, it is necessary to use the information on timbre sub-spectra, i.e. on the sub-spectra of the total spectrum of the acoustic signal generated by one or another modal harmonic.

Summary
Automated monitoring systems have found application in the construction of buildings and structures. So, the installation of sensors on structural elements and the collection of information from them will make it possible to determine changes and deviations from the permissible values.

When analyzing the changes in the used building materials and the presence of zones of no connection determined by the system using piezoceramic sensors in them, the oscillations amplitude and spectrum will change. Closely located defects cause the appearance of lower frequencies in the spectrum of natural oscillations and an increase in the reflected signal amplitude in comparison with the defect-free regions of the sample. On the contrary, deep-seated defects cause the appearance of higher frequencies in the oscillation spectrum and a decrease in the amplitude of the signal reflected from the defect. Thus, complex monitoring using sensor systems will allow timely decisions on the building overhaul.

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