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Application of full-scale experiments for structural study of high-rise buildings

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Abstract

The paper presents the application of full-scale-model experiments to develop software and design a device for determining the degree of reinforcement bar rusting in concrete elements of high-rise buildings. Operation of the designed device is based on the dependence of the electromagnetic field surrounding a ferromagnetic body on its geometrical parameters and reduction of electromagnetic properties of the ferromagnet by oxidation. To receive primary information about the electromagnetic field an original measuring device is used, which is a matrix of high-precision electromagnetic transducers. In order to determine their position in relation to the control object distance sensors are used. The measurement results are transmitted to a computer model that is adjusted so that the results of modeling the electromagnetic field at the locations of transducers agreed with the results of direct measurements. The required model parameters are the geometric dimensions of the reinforced bar.
To raise the measuring device to the height of the building structure it is proposed to install it on a quadrotor.

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Keywords: full-scale-model experiment; a study of building structures; quadrotor; nondestructive testing of reinforced concrete structures

1. Introduction

Over the past few decades the construction industry has made a significant step forward. Construction technology develops at a fast pace. It should be noted that construction projects vary in purpose, materials, height, standard life service, purpose and operation characteristics. Increasingly, there is a need for renovation of old buildings and

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structures due to changes in their functionality, improvement of design standards, as well as other factors. All this requires the development of a variety of technologies, techniques and special equipment for testing of buildings and structures, as well as quality control of building structures. Engineering survey of building structures is a separate area of construction activities, covering a range of issues related to ensuring the operational reliability of buildings, carrying out the repair work, as well as the development of project documentation for reconstruction of buildings and structures. The amount of the structural surveys is increasing every year, which is primarily a result of deterioration and obsolescence of buildings. Operation of buildings due to various reasons results in the deterioration of building structures, reduction and loss of their bearing capacity, deformation and strains in individual elements and the entire building. To develop measures to restore the performance of structures, it is necessary to carry out control survey operations to identify the causes of premature wear, the bearing capacity reduction. A special class of problems is connected with the examination of high-rise buildings. In this paper, in order to raise the measuring device to the height of the building structure it is proposed to install it on a quadrotor [1, 2].

All nondestructive testing (NDT) methods are based on an analysis of the impact of various types of radiation on the controlled object, the study of the nature of propagation of electromagnetic and acoustic oscillations in it, the study of the structure of materials by conventional and electron microscopes. NDT methods are based on the observation, recording and analyzing the results of the interaction of physical fields (radiation) or substances and the object under control, the nature of this interaction being dependent on the chemical composition, structure of the controlled object, etc. The use of nondestructive testing instruments helps to easily solve the problems of non-compliance with the requirements by the project contractors and the consequences of improper installation.

Depending on the nature of the interaction with the control object, passive and active control methods are distinguished. In the first case waves generating in the object are recorded (by the noise of the operating device it is quite possible to judge its serviceability, failure and even its character). Active methods include the ones based on measuring the intensity of the acoustic signal transmitted or reflected by the object. Currently, the most widely used and promising are active control methods. Depending on the physical phenomena underlying the methods of active control, they are divided into four main types: acoustic, magnetic, eddy-current, radio-wave. Acoustic methods of nondestructive testing such as ultrasonic flaw detectors are applied to all materials conducting acoustic waves. Eddy-current NDT methods are based on the study of the interaction of the electromagnetic field of the eddy current transducer and electromagnetic field induced in the controlled object of the eddy currents having a frequency up to 1 MHz. Eddy-current NDT methods are used in practice to control the objects that are made of conductive materials. Radio-wave NDT methods are based on detection and analysis of changes in the parameters of radiofrequency electromagnetic waves interacting with the object of control (their length ranges from 0.01 to 1 m). They provide the object detection at a depth of 1 m with an accuracy of ± 5 mm. Magnetic NDT methods are based on the analysis of interaction between the control object and the magnetic field. As a rule, they are used to determine the parameters of objects made of ferromagnetic materials. This class of methods is divided into magnetic-particle, fluxgate, induction and magnetic-tape methods.

To study high-rise buildings a measuring device based on magnetic induction tomography (MIT) is proposed. [3]. This method operates on the basis of the principles of magnetic induction non-destructive testing. The method allows visualization of the magnetic permeability distribution based on the interaction of the magnetic field and the ferromagnetic medium. The parameters of the electromagnetic field are determined by the geometrical dimensions of the object and, in particular, they are dependent on the electromagnetic properties of ferromagnetic material, being substantially reduced during the oxidation. In addition, this method is rather powerful in terms of varying the parameters of the radiation to optimize the search and geometric dimensioning of re-bars.

2. Development of the measuring device

To implement the chosen method of nondestructive testing it is suggested to use a measuring device, which block diagram is shown in Fig. 1.

The measuring device includes: OPC – a mini-computer for controlling the measuring process and storing the measurement data for further processing, DAC – a digital-to-analog converter that implements functions of the drive oscillator for signal probing, PA – a power amplifier which provides conditioning of an amplified signal to the DAC output, D – a switch for selecting the emitting coil from the matrix of high-precision electromagnetic transducers (Magnetic System), MA – a multichannel instrument amplifier of EMF signals derived from the outputs of the coils unused for emitting an electromagnetic field, ADC – a multichannel analog-to-digital converter for converting the electric signal into a digital form to be recorded in OPC memory.

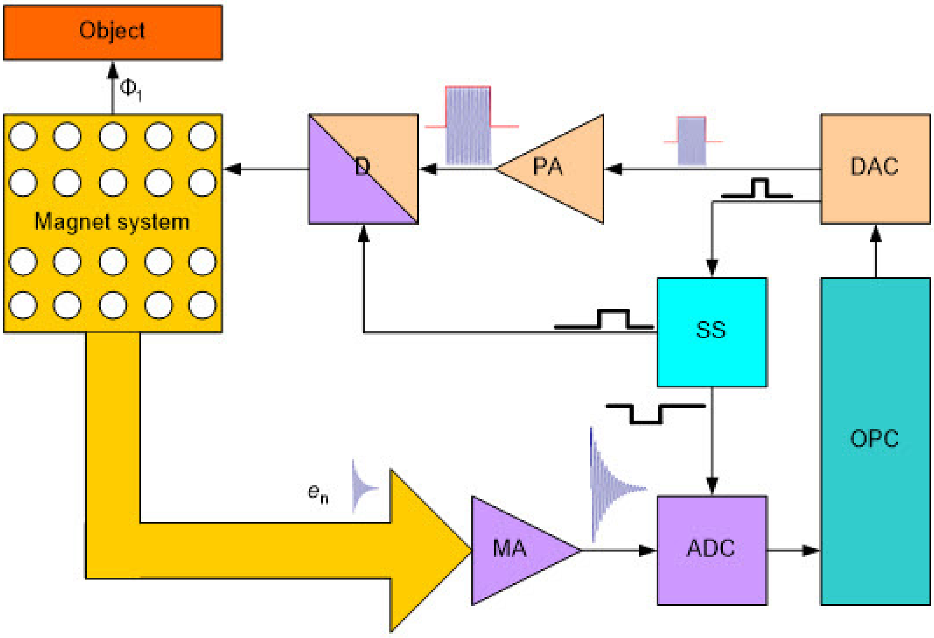

Fig. 1. Block diagram of the measuring device.

Furthermore, the block diagram depicts a timing element SS, intended to synchronize the digital-to-analog converter DAC, the switch D, the analog-to-digital converter ADC.

3. Development of the Magnetic System block

To investigate the possibility of applying the principle of building the Magnetic System block (Fig. 1), simulation of the processes was performed in the GMSH + GetDP application package. Magnetic System block model in conjunction with the test object is shown in Fig. 2. In Fig. 2, the following notations are agreed: 1 – a matrix of electromagnetic transducers, which are induction coils made of stranded copper wire with a *w* number of turns, 2 – the object of control – a test cylinder of iron with a given magnetic permeability μ and dielectric conductivity σ.

A number of experiments were carried out, in each of which electric sinusoidal current was applied to one of the induction coils (Fig. 2, 1.1) and magnetic flux Φ, intersecting the section of the other coils was measured. Examples of the results of measuring magnetic flux Φ as a function of magnetic induction *B* are shown in Fig. 3:

$$\Phi_i = \int B_i(t)dS \ ,$$

where *i* – a sequence number of each of the measuring induction coils.

Fig. 3a, 3b, 3c show simulation results for the induced magnetic flux in the presence of a sample of 12 mm (a red line), 13 mm (a blue line) in diameter, and in the absence of the test sample (green line) in the induction coils marked in Fig. 2, respectively 1.2 (Fig. 3a), 1.3 (Fig. 3b), 1.4 (Fig. 3c) at the frequency of the sinusoidal electric current in the induction coil 1.1 (Fig. 2), equal to 1 kHz. Fig. 3d, 3e, 3f show similar results when the frequency of the sinusoidal electric current in the induction coil 1.1 (Fig. 2) equals 10 kHz.

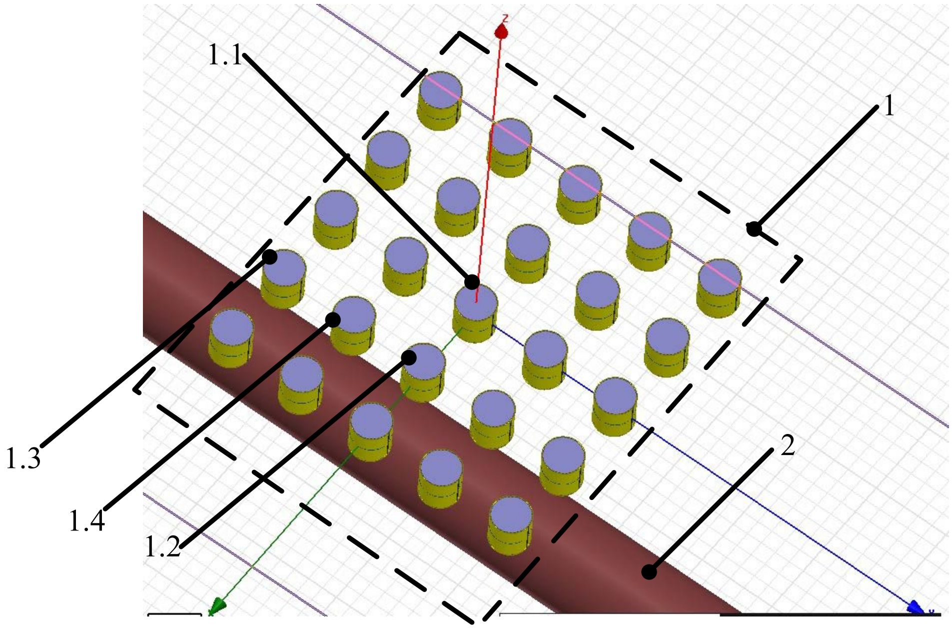

Fig. 2. Model of the matrix of electromagnetic transducers of the measuring device.

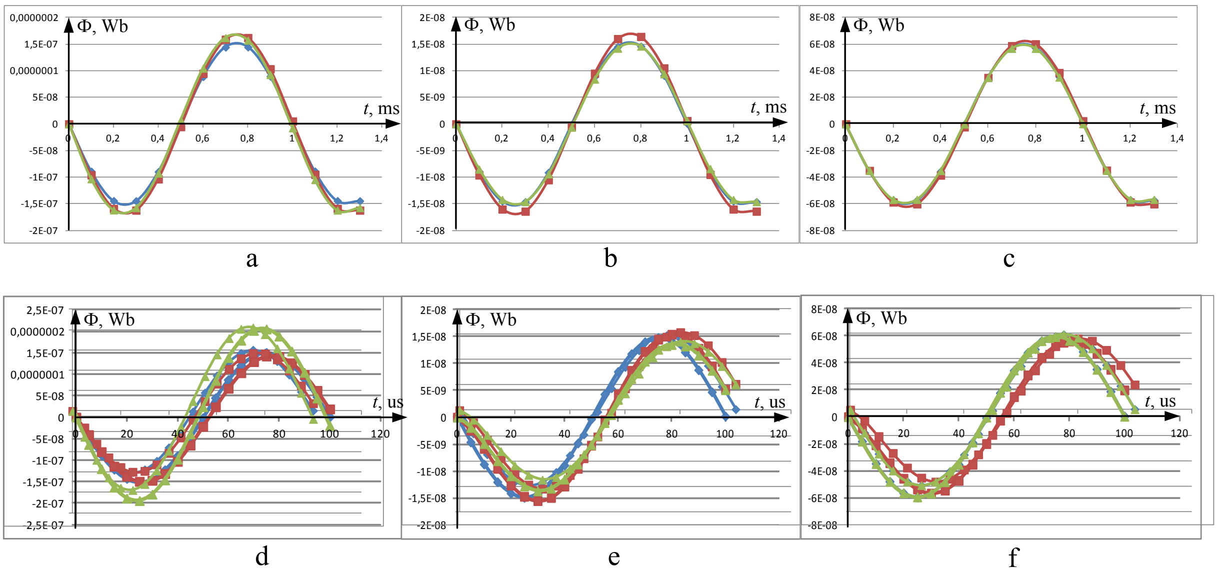

Fig. 3. Examples of the dependencies of magnetic flux on the time $\Phi(t)$, obtained by simulation in GMSH + GetDP environment for various measuring induction coils.

For processing of the received aggregate time characteristics from all the induction coils we suggest to use the original method of full-scale-model experiment.

4. Application of the full-scale-model experiment to determine the parameters of the ferromagnetic elements of reinforced concrete structures

It is suggested to analyse high-rise buildings by means of magnetic induction tomography (MIT) [3]. This method allows visualization of the distribution of magnetic permeability based on the interaction of the magnetic field and the ferromagnetic medium. The magnetic field is generated in the object of study by the system of coils located at its surface. Information on the magnetic properties of the object of study, obtained as a result of the field response, is inputted into a computer. Its software contains a computer model that includes a mathematical model describing the distribution of the field in the object, techniques of modeling and functional minimization. As a result of solving the inverse problem an unknown distribution of the magnetic permeability and geometrical sizes of re-bar inside the object of study is restored, that can be used in nondestructive testing of concrete elements in high-rise buildings. This problem belongs to the inverse problems of mathematical physics.

To solve such a problem it is advisable to use a methodology of full-scale-model experiment. The effectiveness of this approach for determining the magnetic parameters of electrical products is shown in [4, 5]. The special feature of this methodology is that the results of the experiment are used as the input data for simulation of the electromagnetic field of the test structure, and as a criterion for assessing the accuracy of the numerical solution to this problem.

To solve the problem we propose the following algorithm for a full-scale-model experiment in MIT:

1. A magnetic field is generated by applying a current pulse to excitation winding V_{obm} and magnetic induction B_i^* $(i = 1,2,...,N)$ is measured, where N – a number of measuring transducers.

2. We set the initial values of the magnetic permeability of the subdomains of the test object μ_i^0 and the geometrical parameters g_i^0

$$\vec{f}^{\,0} = \left(\mu_1^0, \mu_2^0, ..., \mu_{m1}^0, g_1^0, g_2^0, ..., g_{m2}^0\right).$$

3. We solve the direct problem.

The magnetic field equation has the form of

$$\text{rot}\vec{H} = \vec{\delta}\,;\ \text{div}\vec{B} = 0\,, \tag{1}$$

wherein $\vec{B}$, $\vec{H}$ – vectors of the magnetic flux density and magnetic field strength, respectively, $\vec{\delta}$ – the known current density in the excitation winding V_{obm}.

For the system (1) $\vec{B} = \mu_0 \vec{H}$ – in the air V_0 and in the excitation winding V_{obm}; $\vec{B} = \mu_{Fe}\vec{H}$ – in ferromagnets V_{Fe}; $B_n^+ = B_n^-$; $H_\tau^+ = H_\tau^-$.

On the basis of the equation $\text{div}\vec{B} = 0$, we introduce the magnetic vector potential $\vec{A}$ by relations $\text{rot}\vec{A} = \vec{B}$; $\text{div}\vec{A} = 0$. Using $\vec{A}$, we transform the system (1). As a result, we obtain

$$\text{div}\left(\frac{1}{\mu_0}\text{grad}\vec{A}\right) = \begin{cases}\vec{\delta} - \text{ in } V_{\text{obm}}; \\ 0 - \text{ in } V_0;\end{cases} \qquad \text{div}\left(\frac{1}{\mu}\text{grad}\vec{A}\right) = 0 - \text{in } V_{Fe}\,. \tag{2}$$

At the interface we have

$$A^{+} = A^{-}; \ \frac{1}{\mu^{+}}\frac{\partial A^{+}}{\partial n} = \frac{1}{\mu^{-}}\frac{\partial A^{-}}{\partial n}. \quad (3)$$

The solution of system (2) with condition (3) can be conveniently found by using the variational version of the finite element method (FEM) [6]. Minimization of the functional corresponding to problem (2), (3) leads to a system of algebraic equations.

$$\sum_{k}\frac{1}{\mu^{k}}\sum_{j}\beta_{ij}^{k}A_{i} = \frac{1}{3}\sum_{k}\mu_{0}\delta^{k}S^{k}, \ k = 1,2,...,N, \quad (4)$$

where $\beta_{ij}^{k} = \iiint_{V^{k}} grad\psi_{i}^{k}\, grad\psi_{j}^{k} dV$, ψ_{i}^{k} and ψ_{j}^{k} – the basic functions of the k-th finite element; S^{k} – area of the face of the k-th finite element.

After solving the system (4), we find B_{i}^{0} $(i = 1,2,...,N)$, where N – a number of measuring transducers.

1. Calculate the square of the norm of the difference $J_{i} = \left\| B_{i}^{0} - B_{i}^{*} \right\|^{2}$.

2. Check the condition $J_{i} \leq \varepsilon$, where ε – accuracy of determining the minimum of the functional J_{i}.

3. If the condition of point 4 is satisfied, the solution is obtained and it equals $\vec{f}^{0}$. Otherwise, using the gradient method of minimizing the functional J, we find the next approximation $\vec{f}^{1}$. Here ratio $\vec{f}^{k+1} = \vec{f}^{k} - [\alpha]\mathrm{grad}J^{k}$ is used, wherein $[\alpha]$ – a diagonal matrix of steps.

4. Return to point 3, using the new $\vec{f}$ values.

5. Conclusion

An algorithm was developed to implement the method of full-scale-model experiment as the basis for the software and design of a device for determining the degree of reinforcement bar rusting in concrete elements of high-rise buildings. To get raw information about the electromagnetic field an original design of the magnetic system, which is a matrix of high-precision electromagnetic transducers was proposed and studied. The measurement results undergo processing in a computer model, which is set in such a way that the result of a simulation of the electromagnetic field at the locations of transducers should coincide with the results of direct measurements.

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