Study of the relationship between the parameters of electromagnetic-acoustic transformation and the stress-strain state of the metal to solve the problem of remote monitoring of power equipment

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Abstract. The implementation of Russia's energy strategy provides for the creation of an intelligent control system for active-adaptive electrical networks of the electric power complex, which contains a system for remote diagnostic monitoring of energy equipment, including metal load-bearing structures of electrical energy generation, transmission and consumption facilities. Promising in this regard is the use of a high-performance electromagnetic-acoustic method, which allows non-contact detection of metal defects and monitoring of their stress-strain state. But existing electromagnetic-acoustic diagnostic tools do not have sufficient sensitivity and information content to solve this problem. The article presents the results of experimental studies aimed at identifying and processing informative parameters of electromagnetic-acoustic transformation for the implementation of remote diagnostic monitoring of the stress-strain state and metal damage of power equipment. Based on the research results, it was proposed to use a frequency model formed as a result of spectral analysis of the electromagnetic-acoustic transducer signal as an integral parameter characterizing the state of the metal.

1 Introduction

Any power plant contains various dynamic or static metal structures, the technical condition of which largely determines the reliability and safety of the entire power complex. According to the territorial bodies of Rostechnadzor for 2021, the main technical causes of accidents at supervised power plants were: “wear and tear of equipment during long-term operation; manufacturing defects in equipment leading to mechanical damage, destruction of equipment and possible fire;” while noting “a significant increase in the total number of accidents by 47% (10 accidents) compared to the same period in 2020.” An analysis of the causes of accidents at energy facilities associated with the destruction of equipment shows that destruction most often occurs due to exceeding the design loads in

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local zones of concentration of mechanical stresses, weakened by various damages. In zones of concentration of mechanical stresses, conditions are created for the emergence of microdefects and the process of degradation of the structural properties of the metal is started. Microdefects develop into macrodefects leading to equipment destruction [1]. The results of the investigation into the causes of the largest accident in the history of Russia at hydropower facilities - at the Sayano-Shushenskaya HPP, which occurred in 2009, showed that most of the studs securing the turbine cover of the hydraulic unit were destroyed under the influence of dynamic mechanical loads, and the studs at the time of destruction already had fatigue damage [2].

Modern diagnostic tools for power equipment are focused on identifying already developed metal defects that are unacceptable according to regulatory documents, but this is not enough to prevent equipment destruction. Diagnostic tools are needed to identify areas of increased concentration of mechanical stress and microdefects at the level of the metal structure. Therefore, the development of new and improvement of existing methods for diagnosing the stress-strain state (SSS) and identifying microdefects in metal is an urgent task.

The electric power complex of Russia, in accordance with the country's ongoing energy strategy, is undergoing a deep modernization using the innovative organizational and technological platform IES AAS (intelligent power system with an active-adaptive network), which is a unified energy information complex with intelligent control and continuous monitoring of the technical condition and operating mode of all its elements. The technical condition of electrical equipment is monitored by a remote diagnostic monitoring system. To implement remote diagnostic monitoring of the stress-strain state of equipment, appropriate highly sensitive and highly informative diagnostic tools are required. Currently, there are a large number of diagnostic tools that implement various physical principles for monitoring mechanical stress. These diagnostic tools are recommended for industrial use; there are regulatory documents regulating their use [3-7]. But their practical application in real production conditions is hampered by the ambiguity and nonlinearity of the relationship between the magnetic, acoustic and mechanical properties of metals. The control results are influenced by the structure and chemical composition of the metal, the dimensions of structures, protective coatings, mechanical history, and the presence of micro and macro defects. A promising method for monitoring the stress-strain state is the use of electromagnetic-acoustic (EMA) conversion, which makes it possible to implement high-performance non-contact diagnostic tools [8-11]. Existing electromagnetic-acoustic diagnostic tools, due to the double mutual conversion of electromagnetic and acoustic waves, are significantly inferior in sensitivity and accuracy to acoustic tools with traditional contact piezoelectric transducers. A literature review revealed many publications of research results aimed at increasing the sensitivity and information content of the electromagnetic-acoustic monitoring method [12-15]. Of particular interest are research and development on non-contact testing of extended and large-sized metal structures by scanning them with acoustic waves generated by electromagnetic-acoustic transducers [16]. But these studies are mainly aimed at improving the design of electromagnetic-acoustic converters and developing new methods for isolating and processing information contained in the parameters of acoustic waves. The information potential of the electromagnetic component of the electromagnetic-acoustic transformation has not been fully explored to date.

In [17], to improve the EMA testing method, it was proposed to use a dynamic mathematical model of the test object in operator form - the transfer function $W(p)$ - as an integral parameter characterizing the stress-strain state and damage to the equipment metal. The integral parameter in the process of changing the stress-strain state of the metal continuously changes and reflects the change in the totality of the mechanical, acoustic and...
electrical properties of the metal. But for all its information content, the dynamic mathematical model in practical application is characterized by significant labor intensity and does not exclude the influence of the human factor on the control results. For practical applications, frequency models of the stress-strain state and damage of metal are preferable, allowing the use of an effective spectral method of information processing [18]. The use of frequency models, due to the large amount of initial information that needs to be processed, is based on modern intelligent neural network technologies.

The purpose of the work is an experimental study of the informative parameters of electromagnetic-acoustic transformation and methods of their processing to solve the problem of non-contact monitoring of the stress-strain state and damage of metal of power equipment.

2 Materials and methods

Experimental studies of informative parameters of EMA transformation and their relationship with the stress-strain state and microdamage of metals were carried out using the methodology and information-measuring complex described in [19]. Metal samples for research were selected based on an analysis of the range of metals used in power engineering. Standard samples are made of steel grades St3sp and 09G2S in accordance with GOST 1497-84 Metals. Tensile test methods. The studies were carried out using a Walter + Bai LF TTM-600 testing machine (Figure 1).

Fig. 1. Walter + Bai testing machine.

For non-contact generation of ultrasonic waves, reading and filtering of the reflected electromagnetic-acoustic signal, an EM4000 thickness gauge-flaw detector with ScanView software was used. Spectral analysis of the electromagnetic-acoustic transducer signal was carried out using WinPOS “Expert” software. Metallographic analysis and registration of changes in the structure of steels during testing of samples were carried out using a metallurgical microscope Micromed MET S.
3 Results and Discussion

In Fig. Figure 2 shows a tensile diagram of a sample made of St3sp steel with marked control points O, B’, C’, D’, E’, K’, P’, at which the properties of the metal change significantly. The diagram also shows points A, B, C, D, E, K, P to which the samples were loaded taking into account reversible deformation. The same figure shows samples made of St3sp steel and photographs of the microstructure of these samples, corresponding to their residual stress-strain state at the control points of the tensile diagram.

![Tensile diagram of a sample made of St3sp steel with photographs of the microstructure at control points.](image)

For control points of the tensile diagram, using the method of moments, dynamic mathematical models of samples $W(p)$ were obtained [20-21]. By replacing the operator $p$ with $j\omega$ in the dynamic models, we obtained the corresponding frequency models of the SSS samples - amplitude-phase frequency characteristics (APFC):

$$W(j\omega) = \frac{Y(j\omega)}{X(j\omega)} = K \frac{b_0 + b_1(j\omega) + ... + b_m(j\omega)^m}{a_0 + a_1(j\omega) + ... + a_n(j\omega)^n} = K \frac{B(j\omega)}{A(j\omega)},$$

Where $Y(j\omega)$ and $X(j\omega)$ are the response and impact signals of the electromagnetic-acoustic transducer in frequency form; $B(j\omega)$ and $A(j\omega)$ – numerator and denominator polynomials, $K$ – transmission coefficient; $a_i, b_i$ – coefficients of the numerator and denominator polynomials.

Figure 3 shows the amplitude-phase frequency characteristics of a sample made of St3sp steel in the initial state and residual stress at point D’ of the tensile diagram.
Amplitude-phase frequency characteristics shown in Figure 3 clearly demonstrate that with a change in the stress-strain state and damage to the metal structure, a change in frequency patterns occurs. Each point of the tensile diagram has its own frequency model, which allows it to be used to identify the stress-strain state and damage of metals. To form a frequency model of the stress-strain state and damage to the metal of power equipment, the parameters of the harmonics of the pulse signal of the electromagnetic-acoustic transducer are used, obtained by expanding into a Fourier series using the WinPOS “Expert” measurement information processing program. To identify the stress-strain state and damage of the metal using a frequency model, an artificial neural network (ANN) has been developed and trained.

The development of the artificial neural network was carried out using the C# programming language, the Microsoft Visual Studio development environment, and the ML.NET library based on the .NET framework. To identify the stress-strain state of a metal sample, an intelligent data classifier was used, which solves the problem of multi-class classification. To process data, an artificial neural network classifier uses polynomial logistic regression. An artificial neural network is trained using a “supervised” method. The vectors of the training set are presented as input to the artificial neural network, errors are calculated and weights are adjusted for each vector until the error reaches an acceptably low level.

The structure of an artificial neural network based on a polynomial logistic regression model is shown in Figure 4, it contains 3 layers:
- Input layer.
- Hidden, computational layer.
- Output layer, target function.

It has been experimentally established that to achieve acceptable accuracy in identifying the stress-strain state and damage to the metal of power equipment, taking into account the required signal-to-noise ratio, it is sufficient to use the parameters of the first 15 harmonics of the electromagnetic-acoustic transducer signal. As informative parameters of the harmonic components, their amplitudes in decibels and phases in radians are taken. A data sample is generated in MS Excel format for further loading into an artificial neural network for its training. Data from the input layer enters the hidden layer, where the values of the elements of the weight matrix and the bias vector are calculated. Logits are vectors of the original (unnormalized) predictions generated by the classification model. When solving a classification problem, logits become input data for the activation function - softmax. The softmax function generates a vector of normalized probabilities with one value for each possible class.
The states of the softmax activation function correspond to 8 specified states of the output neurons, which determine the highest probability of belonging to one of the 8 ranges between control points on the stretch diagram. During the artificial neural network training process, the ML.NET automatic model builder selects the optimal model for the provided data set. After loading the training set, ML.NET examined 183 models and identified the best one, the accuracy of which reaches 92.16%.

When loading the results of experimental measurements of the harmonic parameters of the electromagnetic-acoustic transducer signal to the input of the intelligent model, it determines to which interval between the control points of the tensile diagram the stress-strain state of the metal sample under study corresponds.

4 Conclusion

Early identification of the stress-strain state and damage to the metal structure of power equipment makes it possible to prevent accidents associated with equipment failure and destruction.

Based on the research results, it is proposed to use frequency models obtained on the basis of spectral analysis of the electromagnetic-acoustic transducer signal to identify the stress-strain state and damage to metal equipment. The use of an artificial neural network makes it possible to simplify the process of identifying the stress-strain state and damage of metal, increase its reliability and, accordingly, the reliability and safety of operation of energy complexes.

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Fig. 4. Structure of an artificial neural network.
References


12. C. Jiang, Z. Li, Z. Zhang, S. Wang, New Design to Rayleigh Wave EMAT Based on Spatial Pulse Compression. Sensors (Basel), 23, 8, 3943 (2023)


18. M.G. Bashirov, E.M. Bashirova, I.G. Yusupova, D.Sh. Akchurin, Investigation of ways to increase the efficiency of electro-magnetic-acoustic transformation of diagnostic tools for energy equipment, Industrial power engineering, **10**, 2-9 (2022)

19. M.G. Bashirov, E.M. Bashirova, I.G. Yusupova, V.O. Dratsky, A.I. Murtazina, S.A. Kvachinsky, Modeling and experimental investigation of the influence of mechanical stresses and metal damage of oil and gas equipment on the parameters of electromagnetic-acoustic transformation, Oil and gas research, **21**, 1, 183-194 (2023)
