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SYNTHESIS OF MATHEMATICAL MODELS FOR MONITORING THE TECHNICAL CONDITION OF VEHICLES DURING THEIR OPERATION

Introduction

Monitoring the technical condition of vehicles during their operation consists in their continuous maintenance and diagnostics during periodic repair work. The reliability and operability of vehicles depends on the quality of monitoring. At the same time, in the process of operation, in the conditions of uncertainty of the nature and magnitude of the loads, the properties of materials deviate from their normative values, which requires periodic equipment shutdowns and diagnostic work. The need to take into account a larger number of various indicators and the low quality of predictive estimates force us to turn to mathematical modeling and its simulation component to assess their suitability for certain types of vehicle monitoring.

The synthesis of mathematical models for monitoring the technical condition of elements of transport equipment during their operation depends on the completeness and quality of available a priori information. However, the uncertainty of the nature and magnitude of loads during the operation of complex structures complicates the use of existing information and requires further experimental research and the development of mathematical models of technical monitoring based on them.

Forecasting and issuing conclusions about the results of the technical condition of vehicles on the basis of technical diagnostics, as well as the assessment of the residual resource is the most vulnerable link of technical activity in accordance with regulations and standards.

Formulation of the problem

One of the problems of mathematical modeling of monitoring the technical condition of vehicles is the lack of practical recommendations on the use of different types of modeling for specific diagnostic tests. Another problem is the lack of quantitative characteristics of the results of diagnostic works with mathematical justification and the selection of appropriate models of the functioning of transport systems.

The purpose of the work is the synthesis of mathematical models of continuous processes and the determination of the possibility of their use for monitoring the technical condition of vehicles during their operation.

Literary review

Technical diagnosis, according to regulatory documents, is a determination of the technical condition of the object. This is a higher level of assessment of the remaining resource compared to methods of non-destructive testing and defect inspection [1]. The term technical diagnostics means the field of knowledge about establishing the technical condition of the object [2]. It is implemented in the form of establishing patterns of changes in operational characteristics [3,4,5]. Its task includes searching for locations and causes of malfunctions and forecasting the current state [6,7]. Monitoring consists in observing and checking the quality of equipment. In the conditions of work with large data flows, there is a very high probability of errors in conclusions about the results of diagnostics [8]. Therefore, along with statistical models of diagnostic information processing, priority should also be given to probabilistic methods, Markov chains, etc. [9].

Mathematical models for monitoring the technical condition of structures under load are based on the general principle of converting the degradation of the structure into a fixed signal of a different nature [10, 11]. This can be the localization of the defect, which is manifested in the single act of the appearance of cracks in the form of a pulse of finite length and the development of the defect under load, which is manifested in the form of a series of continuous events [12].

Mathematical models describing the monitoring of the technical condition of objects should describe in detail the internal and external characteristics of the processes of interaction with the environment of their functioning. This class of models is classified as imitation.

Presentation of the main material

The classification of mathematical simulation models from the point of view of the mechanism of monitoring the operational properties of transport equipment is presented in Fig. 1.

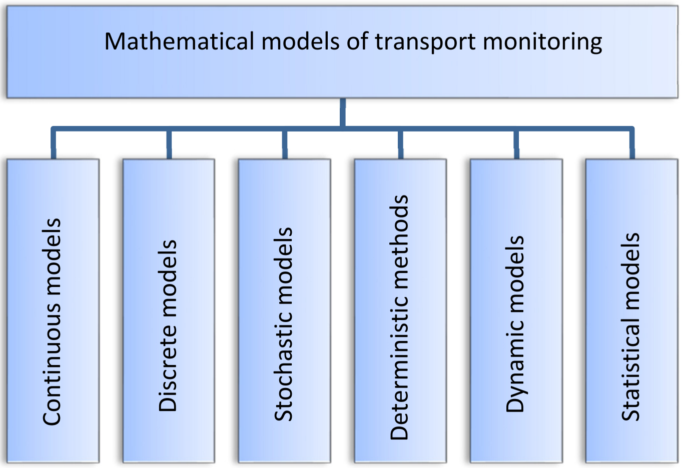

Fig. 1. A variety of mathematical models of intelligent monitoring of operational properties of transport devices

The structuring of mathematical models presented in Figure 1 is considered as informational support for intelligent monitoring of changes in the properties of transport objects, each of which has a specific purpose.

The statistical model is built on the basis of experimental data on the interaction of input and output variables, reflecting layouts of the location of elements in real structures. A statistical model is a kind of slice of information that changes over time. It includes a set of statistical assumptions related to the generation of sample data and is applied in cases where there is a certain level of uncertainty in the data stream caused by the influence of external factors and measurement errors. The method of implementation and presentation of statistical simulation modeling data includes analysis and visualization of the general population. Mathematical expectation, root mean square deviation, statistical moments are used as characteristics. Choosing a statistical model requires knowledge of the process itself and the appropriate statistical analysis.

Quantitative information about a real data set is represented by statistical moments, data processing by the method of least squares, correlation coefficients.

A statistical moment is a numerical characteristic of the distribution of a random variable x, expressed as the frequency of occurrence v_k of a certain event, determined by the formula

$$v_k = \int_0^\infty x^k f(x)dx,$$

where k – natural number

Most often, the first and second moments are used, that is, the mathematical expectation and variance.

The method of least squares is used to solve problems of minimizing the sum of squares of deviations of some functions from experimental data.

Let's introduce the following notation: y_i – set of experimental data, $y_i - f(x_i, \beta)$ measurement error, $f(x, \beta)$ is a linear scalar function, and β – unknown parameter. Then the solution of statistical modeling will be reduced to finding such a value of the parameter β that the totality of the measurement error is minimal

$$S_\beta = \sum_{i=1}^{n} (y_i - f(x_i, \beta))^2 \rightarrow \min.$$

Estimates of correlation coefficients are based on the analysis of statistical data, which are random variables. For the pairwise correlation model between variables x and y, the correlation coefficient r is calculated using the formula

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(x_i - \bar{x})^2 \sum_{i=1}^{n}(x_i - \bar{x})^2}},$$

where $\bar{x}$ and $\bar{y}$ average value of the variables

As for the monitoring of operational properties, they can be used in static tests, tests on bending, stretching, and torsion.

Dynamic models reflect the interaction of elements of transport devices in a reduced form. Their feature is external functional similarity. A variety is analog models, in which the properties of a real object are identical to other properties. Dynamic models contain information about the behavior of the system and its constituent elements. These models may contain a description of phases, process development, and a state diagram.

Thus, the dynamic model of the temperature in the room can be represented by the equation

$$\frac{dT_{room}}{dt}=\frac{1}{m_{room}c_{air}}\left[\frac{dQ_{gain}}{dt}-\frac{dQ_{loss}}{dt}\right].$$

Where m_{room} – air mass in the room, c_{air} – heat capacity of air, $\frac{dQ_{gain}}{dt}$ – heat flow or heat flow power, $\frac{dQ_{loss}}{dt}$ – heat flow in units of time.

As for the monitoring of experimental properties of transport objects, this property can be the propagation speed of ultrasonic vibrations, coercive force, and thickness measurement.

Deterministic methods are based on the interaction of management influences and machine computing components of information recording devices. Such models allow us to handle complex situations in which there are many solutions and constraints. They are especially useful when the model reflects real physical processes and laws. In such models, the analytical representation of regularities and the basic mathematical apparatus are expressed in the form of differential and integral equations.

The transformation of discrete signals caused by stress in the structure of materials into a continuous analytical function is possible using Fourier series

$$\int_{v}\frac{dv}{dt}=\int_{v}\rho f dv+\int_{s}\sigma_n ds$$

$$\int_{V}\rho\frac{d}{dt}(r\times v)dV=\int_{V}r\times\rho f dV+\int_{S}r\times\sigma_n dS,$$

where ρ – material density, v – rate of propagation of oscillations, S and V surface, V – unit cell volume, r – distance from the origin of coordinates, f – single effort.

If we put the Cauchy equation into the Ostrogradsky-Gauss formula, we get

$$\int_{V}\rho\frac{dv}{dt}\mathrm{d}V=\int_{v}f\rho\,\mathrm{d}V+\int_{s}\sigma_n dS,$$

where n– single normal.

The components of the stress tensor can be represented in the Cartesian coordinate system

$$\sigma=\left\|\begin{matrix}\sigma_x\tau_{xy}\tau_{xz}\\ \tau_{xy}\sigma_y\tau_{yz}\\ \tau_{xz}\tau_{yz}\sigma_z\end{matrix}\right\|.$$

Components σ_x, σ_y, σ_z is the normal stress, components τ_x, τ_y, τ_z – tangential stresses

The equations of disturbances caused by experimental or peak loads take the form

$$\begin{cases}\frac{\partial\sigma_x}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}+\frac{\partial\tau_{xz}}{\partial z}+\rho f_x=\rho\frac{dv_x}{dt}\\ \frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\sigma_y}{\partial y}+\frac{\partial\tau_{yz}}{\partial z}+\rho f_x=\rho\frac{dv_y}{dt}\\ \frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\sigma_z}{\partial z}+\rho f_x=\rho\frac{dv_z}{dt}\end{cases}.$$

The creation of digital platforms provides data collection and processing, analytics for assessing the condition of the object of diagnosis. In its practical basis, the digitalization of diagnostics is based on complex interconnections of information elements based on monitoring and processing of a large array of experimental data in the digital space. The use of digital duplicates of field tests allows to study the loading processes of transport structures during their operation in the form of digital copies. The use of digital doubles makes it possible to significantly reduce the number of field tests and the time to diagnose the causes that cause deviations in operational parameters.

As for the monitoring of operational properties of transport objects, such models can be used as a replacement for analytical representations with digitization and hybrid models, which are the most modern and promising monitoring models.

With stochastic modeling, it is not necessary to transform the mathematical model into a system of equations with respect to the original values. It is enough to simulate models while preserving their logical structure using experiments on real objects. A simulated stochastic model for monitoring the technical condition of vehicles during their operation is considered to be a model in which the functional states between elements carry elements of randomness described by probability laws.

Such modeling is appropriate when there is no complete mathematical model, or the analytical procedure is time-consuming. The use of this type of models allows you to observe the dynamics of the process. A distinctive feature of such modeling is the ability to change the sequence of events in the system.

A typical representative of such modeling will be Markov chains. In Markov chains, the probability P_{ij} of the transition of the system from state E_1 to state E_2

$$P=\begin{vmatrix}P_{11} & P_{12}\cdots & P_{1n}\\ P_{21} & P_{22}\cdots & P_{2n}\\ P_{n1} & P_{n2}\cdots & P_{nn}\end{vmatrix},$$

A sequence of random variables $\{S_k\}_k$ is called a Markov chain if

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$$P\big(S_{k+1} = i_{k+1} \,|\, S_k = i_k;\\ S_{k-1} = i_{k-1} ..., S_0 = i_0\big) =\\ = P\big(S_{k-1} = i_{k-1} \,|\, S_k = i_k\big).$$

Here P is the probability of state i at step k, $\{S_k\}$ − space of states, k − step number

The interpretation of this form of record looks like the distribution of subsequent states depends only on the current state and depends on the previous one. In the stochastic model of bases on Markov chains, a sequence of random events with a finite number of states, the probability of each state reached in the previous state determines its future state.

A random process causing a state change is described by a transition P with elements P_{ij}, where $i, j \in I$. Taking into account these conditions, P_{ij} is the probability that the system will be in state j provided that at the moment she is in state i

$$0 \le P_{ij} \le 1 \quad \forall i, j \in I \to .$$

The probability P_{ij} can be found according to Markov's inequality

$$P_{ij}(n) = \sum P_{(m)} P_{(n-m)}$$

where m – number of steps of the system during its transition from the state i to state j

The use of graph-theoretic methods in multi-agent systems is due to the convenience of commutation of agents as edges of a digraph, the vertices of which correspond to the agents themselves, and the edges to the transitions between them. Orgraph allows you to visualize the structure of the process of monitoring the technical condition of vehicles during their operation and observe the evolution of damage accumulation.

Stochastic models are built on the basis of probabilistic phenomena. The probability distribution functions of the variables underlying the investigated phenomenon and random excitations are calculated. Stochastic simulation modeling preserves the logical structure and sequence of phenomena. In such models, there is no need to compile analytical expressions of the required quantities. This is particularly attractive for estimating the limit state of equipment and estimating the residual resource during its operation.

Discrete simulation models are based on the study of the behavior and functional capabilities of the system in time that exceed the normative ones. The basis of discrete simulation modeling is the implementation of a random process with discrete time, in which all possible states $i_1 i_2$ ... are countable and the transition from one state to another occurs in a jump, i.e. instantaneously, but only at certain points in time $t_1 t_2$ ... called process steps.

A one-dimensional model of a discrete microstructure in the form of point masses connected by elastic bonds [9].

The potential energy of such a system has the form

$$\Phi = \frac{1}{2} \sum_{nn'} (n, n')\, u(n) u(n'),$$

where u – energy in an equilibrium state, n, n' – numbers of interacting particles

The kinetic energy of such a chain

$$T = \frac{m}{2} \sum_n u^2(n, t).$$

The difference between kinetic and potential energy is expressed through the Lagrange function L

$$T = \frac{m}{2} \sum_n u^2(n, t) -\\ -\frac{1}{2} \sum_{nn'} (n, n') u(n) u(n') + \sum_n q(n, t) u(n, t),$$

where $\sum_n q(n, t) u(n, t)$ elastic energy operator

In its general form, the Lagrange equation has the form

$$\frac{d}{dt} \frac{\partial L}{\partial u} - \frac{\partial L}{\partial u} = 0.$$

Taking into account the Lagrange function, the equation of oscillatory motion takes the form

$$m\ddot{u}(n, t) + \sum_{n'} \Phi(n, n') u(n', t) = q(n, t).$$

At the same time, the state of the system changes only at the time of events, and the system is not changed between these states. The functioning of the discrete simulation model occurs in discrete time intervals, organizing the search for the next event. The prospects of this type of models for determining the condition of transport equipment during its operation depends on the fixation of extreme loads that exceed the normative ones.

Continuous simulation models are used for systems that change continuously over time. Models are implemented in terms of derived variables using differential equations. Thus, the differential equation for the state variable S at time t can be written as

$$\frac{dS(t)}{dt} = S^2(t) + t^2; S(0) = k.$$

The first equation defines the speed S as a function of t, the second is the initial condition of the state variable.

As for the monitoring of operational properties, they can be used to describe the rate of corrosion damage. The purpose of this type of modeling is to determine the response of a variable, which is the state of the system, depending on continuous time. By integrating the analytical expressions of the state in time, it is possible to determine the system's response to control influences. The analysis of consideration of the properties of simulation models made it possible to recommend their classification, suitable for monitoring vehicles during operation in real time.

The classification of the main properties of models for monitoring the technical condition of transport devices is given in Table 1.

Table 1

Classification of the main properties of models for monitoring the technical condition of transport devices

Type Signs	Statistical models	Dynamic models	Deterministic models	Stochastic models	Discrete models	Continuous models
Accounting for the dynamics of the time series	Patterns of changes in operational characteristics	Description of process development	Handling complex situations	Determination of system transition estimates	Random processes with discrete time	Continuous time and space
Area of knowledge	Finding locations and causes of malfunctions	Status information	Analytical representations	Probable damage dynamics	Discrete event processes	Accounting for infinitesimally small changes and transitions
Method of implementation	Prediction of the current state	Interaction of elements in a reduced form	Differential and integral equations	Matrix calculation	Search for upcoming events	Derived variables in time
Scope of use	Analysis of statistical data	Description of phases and features	Data processing of physical phenomena and laws	Visualization of the process	Finite sets	Continuous tracking of changes

The presented classification can be an instrumental means of providing diagnostic information and increasing the efficiency of monitoring the technical operation of vehicles, which takes into account the main features and properties of statistical, dynamic, deterministic, stochastic, discrete and continuous models with the specification of the areas of use, the required amount of knowledge, the dynamics of the time series. The synthesis of the main properties of mathematical models for monitoring the technical condition of complex structures presented in Table 1 from the standpoint of various types of diagnostic schemes and their information parameters has a single practical orientation related to the search for emerging defects and their development under the influence of the uncertainty of the nature of the loads.

Of practical interest is the synthesis of mathematical and informational support for monitoring operations of vehicles during their operation, which is the basis of the quality of diagnostic decisions regarding the suitability of products for further use according to their functional purpose.

Regarding the monitoring of operational properties of transport equipment, it can be a reaction to extreme loads.

Summary information on support for monitoring the technical condition of vehicles is presented in Table 2

Table 2

Informational support for monitoring operational properties of transport devices

Statistical simulation modeling	Dynamic simulation modeling	Deterministic simulation modeling	Stochastic simulation modeling	Discrete simulation modeling	Continuous simulation simulation
Field tests, tensile, bending, torsion tests	Control of accompanying identical properties and thickness measurement, coercive force, ultrasound speed, analog models	Establishing the relationship of measurement and calculation values. Replacement of analytical models with digitization and hybrid models	Kinetics of damage accumulation, construction of digraphs in real time	Fixation of extreme loads, performance of interval evaluations	Functional diagnosis, response to load and damage, differentiation of accompanying factors

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The identification of the technological process of diagnosing the state of controlled vehicles is interpreted as the development of a model of the dynamic process of converting the output data of the diagnosis system into information about the state of the material at the time of destruction.

At the same time, it is possible to determine the state of the material at the source of structural damage.

Conclusions

1. A distinctive feature of monitoring the technical condition of elements of transport structures during their intensive operation is the uncertainty of the nature of the loads, which makes it impossible to use traditional methods of diagnosis and encourages to move to their complex use. In these conditions, informational support for conclusions about the suitability of products for further operation and assessment of the residual resource, which is based on the use of various types of simulation modeling, becomes particularly relevant.

2. On the basis of the completed synthesis of mathematical models, analysis of their shortcomings, advantages and possibilities of use for monitoring transport devices during their operation, their main properties were established from the position of their time series, field of knowledge, methods of implementation and rationality of application. Distinctive features have been established and the classification of mathematical models has been performed, which makes it possible to significantly simplify the selection of appropriate models, to ensure the correct use of the mathematical apparatus and analytical ideas about the possibilities of assessing the remaining resource and the quality of monitoring in general.

3. The synthesis of mathematical models for monitoring the technical condition of vehicles during their operation made it possible to establish the limits of their application for specific types and operations of technical diagnostics. Thus, statistical modeling is recommended for mechanical tests for bending, stretching, hardness measurement, dynamic simulation modeling for measuring physical properties: speed, ultrasound, coercive force, deterministic simulation modeling for establishing the relationship between measured and calculated values, stochastic modeling for probabilistic damage dynamics, discrete simulation modeling when fixing extreme loads, continuous operation during the study of functional diagnostics.

Modeling the residual resource of transport devices can be done by creating interactive models that involve a dialogue with the user. The question of which modeling mechanisms should be used is decided by analyzing the advantages in relation to a specific model.

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SYNTHESIS OF MATHEMATICAL MODELS FOR MONITORING THE TECHNICAL CONDITION OF VEHICLES DURING THEIR OPERATION

One of the problems of mathematical modeling of monitoring the technical condition of vehicles during their operation is the lack of practical recommendations regarding the use of various types of modeling for specific diagnostic tests.

A distinctive feature of monitoring the technical condition of the elements of vehicles during their intensive operation is the uncertainty of the nature of the loads, which makes it impossible to use traditional diagnostic methods and encourages to move to their complex use. In these conditions, the informational support of conclusions about the suitability of products for further operation and the assessment of the residual resource of the equipment becomes especially relevant.

The need to create intelligent support for monitoring the technical condition of vehicles during operation is due to the fact that the uncertainty of the nature of the magnitude of loads during the operation of complex structures complicates the use of existing information. The synthesis of mathematical models of the technical state of metal structures, which are based on the general principle of transforming the degradation of the structure into a fixed signal of different nature of origin, has been performed. The presented structuring is considered as informational support for intelligent monitoring of changes in the properties of transport objects, each of which has a specific purpose. The novelty of the structuring of the main models is a practical focus on solving the issues of their functional purpose in relation to test operations in the monitoring and diagnosis of vehicles and the identification of developing defects.

On the basis of the synthesis of mathematical models, analysis of their shortcomings, advantages and possibilities of use for monitoring transport devices during their operation, their main properties from the position of their time series, field of knowledge, methods of implementation and rationality of application were established. Distinctive features have been established and the classification of mathematical models has been performed, which makes it possible to significantly simplify the selection of appropriate models, to ensure the correct use of the mathematical apparatus and analytical ideas about the possibilities of assessing the remaining resource and the quality of monitoring in general.

Keywords: vehicles, technical condition, diagnostics, intelligent monitoring, mathematical models.

Шарко О., Яненко А.

СИНТЕЗ МАТЕМАТИЧНИХ МОДЕЛЕЙ МОНІТОРИНГУ ТЕХНІЧНОГО СТАНУ ТРАНСПОРТНИХ ЗАСОБІВ ПІД ЧАС ЇХ ЕКСПЛУАТАЦІЇ

Однією з проблем математичного моделювання моніторингу технічного стану транспортних засобів в процесі їх експлуатації є відсутність практичних рекомендацій щодо використання різних видів моделювання для конкретних діагностичних випробувань.

Відмінною особливістю моніторингу технічного стану елементів транспортних засобів у процесі їх інтенсивної експлуатації являється невизначеність характеру навантажень що робить неможливим використання традиційних методів діагностування і спонукає переходити до їх комплексного використання. В цих умовах набуває особливої актуальності інформаційна підтримка заключень про придатність виробів до подальшої експлуатації та оцінка залишкового ресурсу обладнання.

Необхідність створення інтелектуального забезпечення моніторингу технічного стану транспортних засобів під час експлуатації пов'язана з тим, що невизначеність характеру величини навантажень при експлуатації складних конструкцій ускладняє використання існуючої інформації. Виконано синтез математичних моделей технічного стану металоконструкцій, в основі яких лежить загальний принцип перетворення деградації структури на фіксований сигнал різної природи походження. Представлена структуризація розглядається як інформаційна підтримка інтелектуального забезпечення моніторингу змін властивостей транспортних об'єктів, кожна з яких є певною метою. Новизною структуризації основних моделей являється практична спрямованість на вирішення питань їх функціонального призначення стосовно операцій випробування в моніторингу і діагностиці транспортних засобів і ідентифікації дефектів що розвиваються.

На підставі виконаного синтезу математичних моделей, аналізу їх недоліків, переваг та можливостей використання для моніторингу транспортних пристроїв у процесі їх експлуатації встановлено їх основні властивості з позиції їх часового ряду, галузі знань, способів реалізації та раціональності застосування. Встановлено відмітні ознаки та виконано класифікацію математичних моделей, що дозволяє значно спростити вибір відповідних моделей, забезпечити коректне використання математичного апарату та аналітичні уявлення про можливості оцінки залишкового ресурсу та якості моніторингу загалом.

Ключові слова: транспортні засоби, технічний стан, діагностика, інтелектуальний моніторинг, математичні моделі.

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