Methods of remote monitoring of operability of mechanical systems

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Abstract. Mechanical systems are widely used in various industries as products of mechanical engineering. Timely identification of the reasons and types of failures is crucial for reliability assurance and safety of the car (machine). The questions of remote monitoring of technical condition of mechanical systems are considered in the paper. Remote monitoring of technical condition and operability of mechanical systems provides possibility of preventing refusals, planning terms and volumes of maintenance operation, repair, and forecasting reliability of cars (machines).

1. Introduction
With the development of modern science and technology, the functions of engineering products are becoming more sophisticated, and the structure of machines is becoming increasingly large-scale, integrated, intelligent and complex. As a result, the number of structural elements of the car significantly increases and requires higher accuracy to ensure the quality of the interface. Complicating the design and the number of elements inevitably leads to an increase in the probability of failures and a decrease in the durability of the car (machine). Severe accidents caused by malfunctions of structural elements are often encountered during the operation of various engineering products. Even a small mechanical malfunction can lead to catastrophic consequences. Remote monitoring of the technical condition and performance is necessary for the timely detection of car (machine) malfunctions. Remote monitoring of the technical state of structural elements is an effective means of predicting reliability and reducing the cost of troubleshooting car (machine) failures [1,2,3,6,8].

Remote monitoring of the technical condition of the car is carried out using remote diagnostics using sensors to control the parameters of key structural elements. Based on the results of a retrospective analysis of the values of the determining diagnostic parameters, it is possible to quantify and assess the current state of key structural elements, to predict the occurrence of possible malfunctions and failures of a car (machine). The introduction of a remote diagnostic system allows one to optimize the maintenance strategy of the fleet of vehicles, significantly reduce the cost of ensuring the reliability and safety of the use of mechanical engineering products [4,5].

2. Mathematical model of monitoring
Any structural element of a car (machine) can be represented in the form of a mechanical system, the main properties of which are organization, controllability and relativity (hierarchy).

The greater dynamic loads a structural element of a mechanical system experiences during operation, the greater the wear rate of critical parts that determine its residual life, the worse its
technical condition, and the greater the deviation of the diagnostic parameters from the nominal range. The deterioration of the technical condition of the mechanical system causes a decrease in the working capacity \( R(t) \), a decrease in the level of failure-free operation \( P(t) \), trouble-free operation, safety, as well as an increase in the aging of the object \( S(t) \). The state space of the mechanical system \( \{S(t)\} \) can be described by a generalized mathematical model of monitoring based on equations of state variables in the following form [3]:

\[
\begin{align*}
\dot{S}(t) &= [A]S(t) + [B]U(t) \\
Y(t) &= [C]S(t) + [D]U(t)
\end{align*}
\]

(1)

where \( \{S(t)\} \) – the vector of aging functions of a structural element with dimension \( I \), each component of which characterizes its generalized structural parameter that varies over time. Through a generalized parameter, this vector characterizes the residual working capacity and the residual life of the structural element;

\( \{S\} \) - aging rate vector (wear, corrosion, decrease of fail safety, safety, failure-free and residual life);

\( \{U_{\text{pk}}(t)\} \) – vector of input actions with the dimension \((p+k)\);

\( \{Y_{\text{d}}(t)\} \) – vector of diagnostic signs of the object’s state, measured by the diagnostic system in the monitoring process.

It is important to note that in the equations of state (1), there is both the structural parameter itself and its first derivative, which is the rate of wear or aging of the object.

The vector of control parameters \( \{U_{\text{pk}}(t)\} \) includes variables characterizing the operating mode of the diagnosed object \( \{U_p(t)\} \) and factors of personnel influence during maintenance and adjustment work \( \{U_k(t)\} \).

The vector of diagnostic parameters \( \{Y_{\text{d}}(t)\} \) includes indicators of temperature, pressure, flow, vibration, etc., as well as diagnostic features, for example, the sum of the amplitudes of the frequency components of vibration.

The mathematical model of the space of technical conditions of a mechanical system can be represented as a set of matrices \([A] \), \([B] \), \([C] \), \([D] \):

\( [m, m] \) – square matrix of the system \([A] = [a_{ij}] \), which completely determines the state of the unperturbed system at \( u(t) = 0 \);

\( [m, (p+k)] \) – rectangular control matrix \([B] = [b_{ij}] \), which determines the influence of the control vector (input vector - parameters of the operating modes and repairs of structural elements) on its state vector;

\( [n, m] \) – matrix of observation results (output matrix) \([C] = [c_{ij}] \), which determines the controllability of the internal state through the available measurement of the parameters of the output vector;

\( [n, (p+k)] \) – transition matrix \([D] = [d_{ij}] \), which determines the direct effect of the input vector on the output vector.

For example, when diagnosing a hydraulic system, matrix \( D \) determines the effect of personnel actions on parameters characterizing changes in the operating mode of the structural elements of the hydraulic actuator or its state by adjusting and repairing during operation.

The parameters of the matrices \([A] \) and \([C] \) are part of the defining criteria for the malfunctions of the object, which are elements of the diagnostic matrix.

The elements of the matrices \([B] \) and \([D] \) are the coefficients of the corresponding regression curves of degradation of the state of the components of the monitoring object, which, as a rule, show a nonlinear relationship between the measured indirect features and the values of structural parameters.
All vectors are slowly changing functions of time in the interval of the life cycle of a mechanical system. The monitoring system (1) is controllable with the coincidence of the ranks of the matrices \([A]\) and \([C]\), and the absence of zero columns in the last.

The dimension of the vector \([S_m(t)]\) (matrix \([A]\)), which determines the degree of real controllability of the state of the mechanical system, is recommended to be selected based on the causes and failure statistics of structural elements of each type. Components \([S_m(t)]\), as a rule, are inaccessible for direct observation, which forces the use of indirect measurement and diagnostic methods. A distinctive feature of the proposed generalized model is the constancy of the control vector \([U_{p+k}(t)]\) during diagnostics, which changes sporadically during start-stop and maintenance of the mechanical system. Between these moments, \([U_{p+k}(t)] = \text{const}\).

The degradation rate \([\dot{S}]\) and the signal \([Y_n(t)]\) have a quasistationary component determined by the last terms of the equations of the system, which change only at the moment of control actions by the personnel. Between these moments, \([U_{p+k}(t)] = \text{const}\).

3. **Signal processing and feature recognition by remote monitoring system**

Advanced signal processing technology is used to isolate functions that are sensitive to specific faults using various signal analysis methods to process the measured parameters. Information on the state of structural elements of the system is contained in a wide range of signals, such as temperature, pressure, flow, vibration, noise, etc. Information about the type and features of a particular malfunction can be obtained using the diagnostic signal recognition method. To ensure compliance with diagnostic requirements, the technology for recognition and analysis of symptoms of malfunctions goes from the analysis in the time domain to the analysis in the frequency domain using the Fourier method. In this case, a linear analysis of stationary signals, non-linear and non-stationary analysis, analysis in the frequency domain, and time-frequency analysis are performed [6].

The system of remote diagnostics and monitoring of the technical condition is equipped with sensors, systems for collecting data, protection against alarms and interlocks, a subsystem for monitoring the state, etc. In addition, the monitoring system requires software for analysis and recognition of diagnostic signals.

When solving problems of recognition and monitoring of the technical condition of structural elements, America BENTLY Corporation 3300, 3500 and DM2000 software, America Westinghouse PDS system, 5911 system developed by ENTECK and IRD, Russian system CAN-WAY, TEXA (Germany), Mitsubishi system MHM (Japan), the B & K 3450 COMPASS system of the Danish company B & K, etc can be used. China has also developed a remote diagnostics and fault monitoring system, which is used on a steam turbine and other industrial equipment [7].

The results of monitoring the technical condition of the mechanical system and the ability to transmit information over long distances to the control center provide the ability to control the reliability and safety of the fleet during operation. Modern means of communication and data transfer allow the use of remote monitoring systems for the rapid assessment of the technical condition of machines (cars) in order to justify control repair actions (see Fig. 1).
4. Conclusions
To control the operability, efficiency and safety of using fleets of vehicles, it is necessary to monitor
the technical condition of the main structural elements. The solution to this problem is possible only
with the help of a remote diagnosis system and the mathematical model presented in the paper.

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