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Multiparameter Approximation Model of Temperature Conditions of Marine Diesel Generator Sets, Based on Markov Chain Monte Carlo

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ABSTRACT: In the article we propose a multi-parameter approximation model, based on Markov chain Monte Carlo, which describes the relationship between the temperature regime, operating conditions and electromechanical parameters of marine diesel generator sets. The approximation model is constructed on the basis of the analysis of experimental data of the exhaust gases temperature of marine diesel generator sets in their long-term operation. As a statistical model of random processes of temperature deviations from the approximation model, a Markov process model is proposed that takes into account the possible correlation of the initial data. Since the measuring channels of modern diagnostic systems are digital, due to discretization in time and level, the studied processes form a Markov chain, which makes it possible to establish the important features of such processes. The use of approximation models ensures the stationarity conditions and the correctness of the proposed Markov model in the conditions of multi-mode operation of marine diesel generator sets. The proposed multi-parameter approximation model, based on Markov chain Monte Carlo, allows you to take into account random perturbations that lead to a random change in the output coordinates of the diagnostic object. The proposed improvement of the model makes it possible to ensure its adequacy to real processes of changing the parameters of the temperature regimes of marine diesel generator sets. The proposed multi-parameter approximation model, based on Markov chain Monte Carlo, can be used in the systems of technical diagnostics of marine diesel generator sets in order to increase the reliability of diagnostic conclusions.

1 INTRODUCTION

Methods of mathematical and computer modeling are currently used at all stages of the life cycle of ship power plants (SPP): in the design, operation and assessment of the technical condition to determine the possibility of further use.

The processes of controlled state changing of such objects are provided by the corresponding on-board monitoring and diagnostic systems (BMDS). For the design of such systems, the use of computer and semi-natural simulators is promising. The use of such simulators can significantly reduce the subsequent stage of bench testing and thereby reduce the cost of its implementation.

The problematic issue of improving the simulator stands is the need to increase the level of adequacy of used mathematical models of the SPP state changing in accordance with the operating conditions. Deterministic mathematical models of processes in SPP, usually used in simulators, do not fully reflect the processes in real objects of control, diagnostics and management, which leads to a discrepancy between the obtained results and real processes. Therefore, the study of methods and means of improving the mathematical models of the controlled change of the

SPP state, which take into account the random nature of such processes, is an actual and important scientific and applied task.

Mathematical models of the processes of a controlled change of the SPP state are based, as a rule, on models of static (throttle) characteristics and piecewise linear dynamic models (PLDM), which sufficiently reflect the dynamics of controlled objects for designing the corresponding BMDS.

The disadvantage of such models is their deterministic nature, that is, the impossibility of taking into account random influences on the change of controlled variables. As a result, the root-mean-square deviation of the values of the controlled coordinates according to the results of tests on the simulator bench and the results of bench tests on a real object can differ significantly even in steady-state conditions. The reason for such significant differences is that the random nature of the processes of the SPP state changing in real conditions is not taken into account value [10]. At present, these scenarios are not taken in databases of such cases, determining outside the agreed risk criteria for the operation of protection and assessing the nature of the risk during the operational mode [11].

The random nature of such processes is a consequence of the action of several factors. Firstly, there is a random nature of external disturbances, for example, for marine diesel generator sets (DGS), changes in load, ambient temperature and other factors. Secondly, there are internal perturbations caused by the processes of energy conversion in the control object. Thirdly, there are always noises of measuring channels. The most significant are the first and second factors, which require their consideration in modeling.

Methods that take into account random perturbations in statistical modeling are known, but their direct application in simulators is impossible, since SPP are multi-mode objects, which does not allow providing the initial conditions for the use of known methods.

Methods for constructing approximation models of complex SPPs based on gas turbine engines (GTE) are considered in the works of the authors [1,2], for ship SPPs in [3]. A technique for constructing a Markov model of a controlled change in the state of complex power plants based on GTE is proposed in [4]. The application of this approach to marine diesel generator sets is proposed in [5]. The present study is mainly based on the works [3, 4, 5] and involves combining the approaches of constructing multi-parameter approximation models and Markov models for deviations of the values of the simulated parameters from pre-formed approximation models. Such an improvement makes it possible to increase the adequacy of models for changing the technical condition of the SPP, in particular, marine diesel generator sets (DGS), under conditions of multi-mode operation and the influence of random factors.

Materials [6 – 9] were used to solve applied problems. Theoretical generalizations and research methods are based on the works [10 – 15].

2 PURPOSE OF WORK

The purpose of the proposed study is to create a statistical model of random processes of deviations in the temperature of the exhaust gases of the cylinders of marine diesel generator sets from the approximation model based on Markov Chain Monte Carlo, which makes it possible to take into account the correlation of the initial data.

3 CONTENTS AND RESULTS OF THE RESEARCH

3.1 *The Approximation Model*

Under the condition of multi-mode operation of the object, the first stage of the proposed information technology is to construct the approximation model corresponding to the object. Such a model reflects the static characteristics (SC) of the control object, that is, the dependence of the initial variables on the control actions in steady-state conditions. If SC are known, then their nature is presented in the passport data of a particular object. If they are unknown, then such dependencies are established directly from the operation data by means of regression analysis. Thus, we obtain the dependences of the initial variables on the controlled actions and loads for possible operating modes. Usually, such characteristics are polynomial in nature. The authors also used more complex neural network models with somewhat better results. Such a multi-parameter model for ship DGSs was proposed and substantiated by the authors in [3].

According to [3], the diagnostic multi-parameter model of the change in the technical condition of the diesel generator set in steady-state conditions during long-term operation has the following form:

$$F_1\left(T_{bx},T_{ex}\right)=F_2\left(\omega,U,I,\eta\right) \tag{1}$$

where:
T_{bx} – air temperature in the ERTemperature inlet,
T_{ex} – reduced temperature.

As justified in [3], to construct a diagnostic statistical model, the load current and the reduced temperature of the cylinder gases can be chosen. However, this temperature is a thermogasdynamic parameter, therefore, as an argument of the statistical model, it is advisable to choose the load moment of the DGS, which is determined from the registration data as follows:

$$M=\frac{P_e}{\omega\eta}, \tag{2}$$

where:
$P_e=UI$ – electric power,
$\omega=n\frac{\pi}{30}$ – angular frequency,
$n=RPM$ – DGS speed,
η – efficiency.

Thus, in the analysis the additional parameters are used in the form of DGS speed and generator voltage, which increases the information content of the model.

The use of a regression statistical model can significantly reduce the dispersion of residual deviations for diesel generator cylinders. As follows from the results of the analysis [3], taking into account the inlet temperature makes it possible to reduce the STD of residual deviations by (10-12)% on average, and the use of the regression model by (2-2,5) times.

The authors believe that preference should be given to such a model for which the dispersion of residual deviations will be the smallest, and which takes into account a large set of recorded diagnostic parameters. The best model may be the one for which the STD of the residual deviations is commensurate with the STD of the measuring channels [16 – 18].

The application of an approximation model makes it possible to take into account the multi-mode nature of the object functioning and in the future to consider only random deviations from the model that make up the time series, the properties of which allow the methods of the statistical model to be applied.

3.2 *Statistical modeling*

At statistical modeling of random processes, the initial hypothesis is belonging to a sample from a general population of independent uncorrelated random variables with some known distribution law, usually a normal distribution. Methods for such modeling using a nonlinear transformation of readings of random variables of a uniform distribution are known. But such a hypothesis about uncorrelatedness is not satisfied in practice [19 – 21].

Since PLDM are used in simulators, in the presence of random perturbations described by the normal distribution law, the resulting random process is Markov [4]. In the steady-state regimes of SPPs, the correlation between neighboring readings is a consequence of the presence of a trend in the initial data. Therefore, the adoption of the hypothesis regarding the Markov nature of processes in SPPs has some advantages for increasing the level of adequacy of statistical modeling.

Measuring channels of diagnostic parameters of SPPs are digital. Therefore, the initial data in statistical modeling is always discretized, both in time and in level. Sampling parameters are set by the applied analog-to-digital conversion method, in particular, the ADC bit depth.

With such a discretization, the model of the generated process is a Markov chain. The dimension of the matrix of transition probabilities can be quite large, but at present this is not a significant factor. If necessary, this dimension can be reduced by forcibly dividing the range of variation of the modeled variable into a set number of intervals, the width of which is determined by the purpose of modeling [22 – 24].

According to the properties of the Markov chain, the final matrix of transition probabilities is formed as a certain step from the matrix of transition probabilities, which makes it possible to construct a dome of probabilities for controlled Markov processes, the form of which can be an important diagnostic feature.

Thus, the algorithm of the proposed statistical modeling has the following form:

- Considers the time series of some initial SPP variable over a long period in conjunction with the time series of changes in the controlled variable or load.
- A regression model of the corresponding variables is formed by a known method.
- The hypothesis of stationarity of the resulting time series of deviations from the regression model is tested using well-known criteria, for example, the Cochrein criterion.
- If it is necessary, discretization by level is performed with a step, which is determined by the purpose of modeling.
- For the time series of deviations, a matrix of transition probabilities of the Markov chain is obtained.
- A matrix of finishing probabilities is constructed and, if it is necessary, a probability dome for a controlled Markov process also is built.
- For simulation tasks in a simulator, the obtained probabilistic dependencies are used to form samples of random disturbances or simulated variables, and for diagnostic tasks they are the basis for the formation of statistically valid conclusions regarding the probability of deviations of variables from passport characteristics.

3.3 *The Applied Problem*

To test the proposed approach, the applied problem of constructing an approximate Markov model for the temperature regime of a diesel generator set during long-term operation was solved.

Following [3], the parameters of daily recording of the operating modes and technical condition of marine diesel generator sets during their long-term operation were considered as initial data. The collection of statistical data on the technical condition of ship DGSs of the NORDSCHELDE bulk carrier with a displacement of 50,000 tons was carried out in the period from 10.16.2017 to 03.27.2018 in various modes of operation of the vessel (navigation, maneuvering, parking with cargo operations). The investigated ship electric power system (SEPS) consisted of three DGSs, which included diesel engines of model 6EY18L manufactured by YANMAR and synchronous generators manufactured by HYUNDAI. The parameters of the DGSs were controlled by two monitoring systems: EPM (Enamor Power Monitor) and Kongsberg K-Chief 600. The EPM system controls and analyzes the electric power parameters produced by synchronous generators (voltage, current, frequency, power, power factor and etc.).

The transmission of the received data is carried out according to the RS 485 standard in the NMEA (National Marine Electronics Association) format to other ship monitoring systems, including the Kongsberg K-Chief 600 main monitoring system. This system controls the diagnostic parameters that determine the technical condition of the ship DGSs. These parameters include: the temperature of the gases of the cylinders, the temperature of the gases at the inlet to the turbocharger, the temperature of the fresh water cooling circuit at the inlet and outlet, and others [25, 26].

According to [3], in order to record the values of diagnostic parameters of ship DGSs, a special electronic table was created, in which their current values were entered every 24 hours. The systematization of the obtained data made it possible to form a common array consisting of 30 parameter vectors, each with a length of 162 values. Data selection made it possible to identify the change in 17 parameters of one of the DGSs with the longest duration of operation from 101 daily slices. Fig. 1 – Fig. 6 shows the results of the implementation of the proposed approach. The initial data and the approximation model are presented in Fig. 1 – Fig. 3.

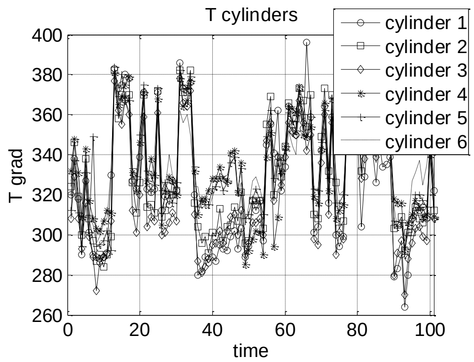


Figure 1. Time series of changes in the temperature of the exhaust gases of the DGS cylinders

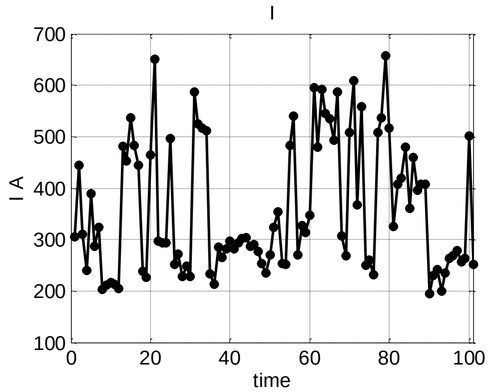
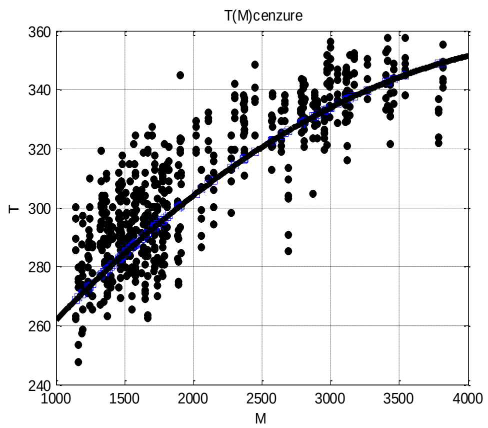


Figure 2. Time series of DGS's load current changes



Figuer 3. Approximation model

Fig. 4 illustrates the initial data for building the Markov model – a time series of deviations from the approximation model, and Fig. 5 – the contour of the matrix of empirical transition probabilities and the line of equal deviations in accordance with the algorithm for generating the statistical model of the Markov chain. Level discretization is chosen as illustrative of 10 degrees.

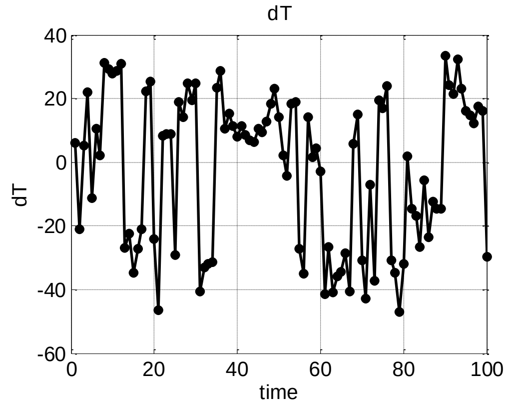


Figure 4. Time series of deviations of the DGS's exhaust gases temperature from the approximation model for the first cylinder

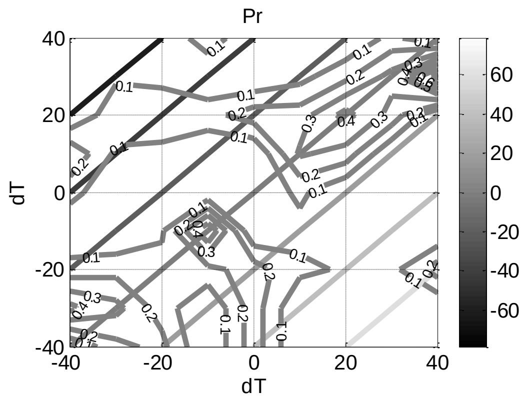


Figure 5. Contour of the matrix of empirical transition probabilities and lines of equal deviations

To check the adequacy of the chosen approach, the final distribution of transition probabilities was constructed and the corresponding data sample was generated in comparison with the original sample. The obtained results are shown in Fig. 6.

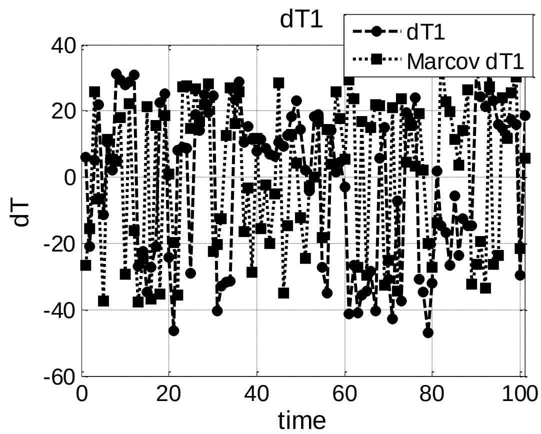


Figure 6. The time series of actual and simulated temperature deviations

As established by the results of a statistical experiment, the difference between the final distribution of transition probabilities of the Markov model and the empirical distribution obtained by known statistical methods is not statistically significant at a confidence level of 0.95 according to known criteria [27]. Therefore, we can assume that the proposed model is adequate to the initial data in accordance with the proposed approach.

4 CONCLUSIONS AND RECOMMENDATIONS

The purpose of the proposed study in the form of increasing the adequacy of the models for changing the state of the SPPs, taking into account random factors, was achieved by using a new information technology, which consists in sequentially performing the stages of preliminary approximation of the time series of deviations of diagnostic parameters from the constructed approximation model, and the stage of statistical modeling.

As the diagnostic parameters, the deviations of which are considered, are selected: the temperature of the exhaust gases of the diesel generator cylinders as the main parameter, as well as: the air temperature at the inlet, the voltage, the load current and the revolutions of the diesel generator [28].

The statistical model of the formation of random processes of such variables deviations from the approximation model is a model of the Markov process. The use of an approximation model expands the possibilities of the statistical modeling method to ensure stationarity conditions and the correctness of the proposed model [29].

The quantitative results are that for the applied example under consideration, the temperature deviations of the exhaust gases of the DGS cylinders from the established limits [3, 6, 7, 9] are not statistically significant and, with an empirical probability of approximately equal to 0.8, are within ±20 degrees.

In contrast to the well-known results [5], the proposed approach to constructing a Markov model for deviations of the temperature of the exhaust gases of the diesel generator cylinders from the constructed approximation model is new.

Prospects for further research may lie in the application of mathematical models of controlled Markov processes.

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