Problems of Improving the Diagnostic Systems of Marine Diesel Generator Sets

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Abstract— **The problem of transition from marine diesel-generator sets operation by the assigned useful life to that by their technical condition is considered. This Article includes a review of control and diagnostic systems of marine diesel-generator sets, establishes their features, analyzes the methods of trend control used and shows their identified shortcomings. A regression statistical model linking the temperature conditions and the load change is offered. The trends of deviations of time series of the temperature condition recorded parameters data from the statistical model in marine diesel generator sets long operation are analyzed. It is proposed to improve the methods of trend control and analysis for use in the systems of technical diagnosing of marine diesel generator sets, in order to increase their efficiency by taking into account the natural wear-and-tear.**

Keywords— ***diesel generator set, diagnostics, trend analysis, feature space, statistical model***

I. Introduction

The current state and development prospects of power plants are characterized by an increasing level of intensity of energy conversion processes in the conditions of strict requirements to the technical and environmental safety. The need to improve technical and economic efficiency in a competitive environment contributes to the introduction of new processes and technologies that require continuous and objective monitoring at all stages. Therefore, in parallel with the increase in the intensity level of energy conversion processes in power plants, the intensity of information processes of continuous assessment and monitoring of their technical condition throughout the life cycle cumulatively increases.

A separate and quite specific class of power plants are diesel generator sets (DGS), which are part of modern marine electric power systems (MEPS).

Distinctive features of such technical facilities are autonomous operation, high maneuverability (continuous mode change), limited energy resources, high risk of emergency situations, high level of responsibility, limited control resources and other factors caused by operating conditions.

The problematic issue of life DGS cycle control is to ensure the required operational reliability. The solution of this problem is achieved by the transition to the operation of MEPS according to their technical condition, which, in turn, requires improvement of both methods of monitoring of the MEPS current state and those for their technical condition long-term forecasting.

A number of mutually contradictory requirements to diagnosis depth, decision-making speed and diagnosis and prognosis accuracy are placed on the methods of diagnosis used in the ship's DGS maintenance and repair planning. One of the main tasks of forecasting the technical condition of ship's DGS is the detection of dangerous defects at the initial stage of their development in order to prevent the occurrence of failures.

Technologies of diagnosing and monitoring of technical condition of MEPS develop in two directions, the first of which is aimed at development of automatic systems for safe management of objects, and the second – at improvement of maintenance and repair processes. The key point in the convergence of the two directions of diagnosis is the necessity to install the stationary monitoring systems on the most important units to solve the problems of prevention of emergency situations arising from control errors, without premature shutdown of the unit. The time available for decision-making on such systems is several times longer than on emergency protection systems, which allows supplementing the system with various monitoring and prediction algorithms, while the amount of diagnostic information used increases several times. This, in turn, permits increasing the reliability of the ship's DGS technical condition forecasts.

Methods of trend control used in modern ship systems of technical diagnostics (STD) allow establishing just the fact of deviation of the registered parameters from their nominal values [1–4], but do not allow giving a forecast assessment of the monitored parameters changes and the probable state of DGS. The DATACHIEF C20 System of KONGSBERG company belongs to such STDs intended for monitoring of current parameters of technical condition assessment [4] of ship power plants (SPP). The operation principle of the well-known [5] ship diagnostic system FAKS (Fault Avoidance Knowledge System) is based on the application of methods of expert assessment of emerging changes in the technical condition of SPP. The monitoring diagnostic system "Watch free system WE22" developed by TERASAKI performs the functions of SPP remote monitoring and control of the current values of parameters that determine their technical condition [6].

The known [7–12] and proposed new [13–16] methods of analysis of recorded parameters time series for solving problems of assessment and forecast of complex technical facilities should be improved taking into account the specifics of the SPP operation, which will increase the reliability of diagnostic conclusions about their technical condition.

II. Purpose of work

The purpose of this work is to substantiate the proposals for finding the feature space elements of the technical condition of marine diesel generator sets in their long-term operation for the subsequent assessment and prediction of their technical condition based on modern proposed trend analysis methods and approbation of such proposals on the example of solving a specific application problem.

This work purpose was being achieved by a number of stages:

– Analyzing the recorded parameters and establishing statistically significant relationships between them.

– Identifying elements of the feature space characterizing the DGS modes change.

– Developing a diagnostic statistical model of DGS mode change and estimation of residual deviations.

– Calculating time series of deviations of DGS parameters from the diagnostic statistical model.

– Analyzing trends in DGS parameters time series deviations from diagnostic statistical model based on the matrix pencil singular decomposition, and

– Forming the diagnostic message.

III. Contents and Results of the Research

A. Analysis of the Recorded Parameters and Determination of their Statistically Significant Relationships

Used as the initial data were parameters of the daily recording the state of the ship's diesel generator sets HFC5 710-14 L with a power of 1875 kVA; the total sample size was 62 daily cross-sections for 23 parameters including the current values of the engine cylinders exhaust gas temperatures. The recorded parameters of the DGS technical condition data were processed in the following sequence: data previewing and sorting; selection censoring; research of dependences; statistical model developing; feature space determining; trend analysis; and the diagnostic message forming.

The analysis of the recorded data of DGS technical condition parameters showed that since 03.04.2016, a dramatic change in operating conditions has taken place, which is illustrated, in particular, by the diagram of power change presented in Fig. 1.

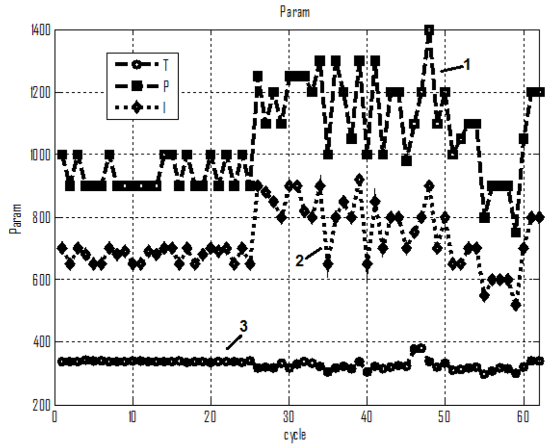

Fig. 1. Change in power, current and average temperature of cylinder exhaust gases of DGS diesel drive:
1 – power changing, kW; 2 – current changing, A; 3 – temperature changing, °C.

The sample was divided into two parts and henceforth, only the second part as the most informative and characterized by significant changes in the DGS load was analyzed in detail. Based on the analysis of the data sample it was found that the various DGS were operated, so analyzed were only the temperature data for DGS No. 2 as the most representative. The sample consisted of 37 daily cross-sections whose distinctive feature was the irregular data collection over time.

B. Selection of the feature space elements characterizing DGS mode changes

The sample subsequent analysis for statistical homogeneity allowed us to establish two cross-sections, which significantly differed from the others by Kolmogorov-Smirnov criterion. The data that did not match the sample properties were excluded from the further analysis. The next step is the correlation analysis of a multidimensional data array.

The distribution of the coefficient of the temperature and load current intercorrelation on the sample for each cylinder are shown in Fig. 2. It was established that there were no load current correlations with other parameters.

As it follows from the results of correlation analysis, the regularities of temperature change for cylinders No. 7 and No. 8 differ significantly from such regularities for cylinders Nos. 1–6.

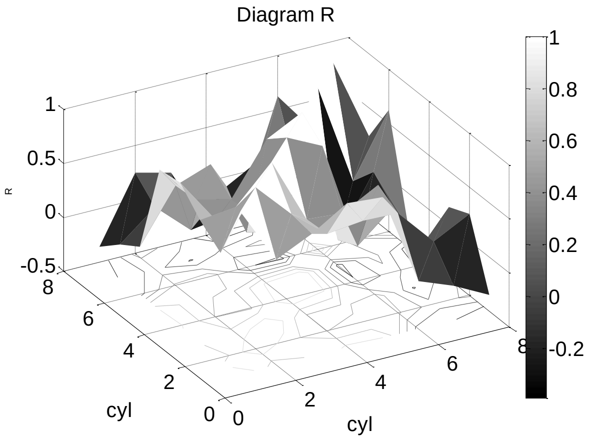

Fig. 2. Distribution of intercorrelation coefficient of exhaust gases temperature of each cylinder

C. Developing the Diagnostic Statistical Model of DGS Modes Change and Estimation of Residual Deviations

The first four cylinders group was chosen to develop a statistical model. The dependence of the average gas temperature of these cylinders on the load on these cylinders is shown in Fig. 3 together with its approximation.

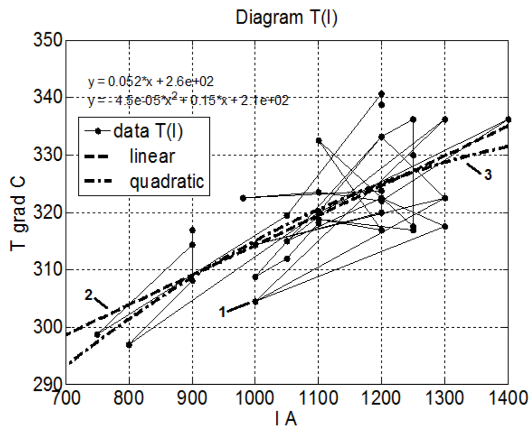

Fig. 3. Dependence of the gas average temperature of cylinders 1 – 4 on the load current and its approximation;
1 – gases average temperature of cylinders 1 – 4;
2 – linear approximation; 3 – quadratic approximation.

The load current was selected as an argument for the average temperature curve (Fig.3) because the scale interval of the recorded power data was too large. A second-order nonlinear approximation was used to develop the regression statistical model, since increasing the statistical model polynomial degree does not reduce the approximation error variance.

The use of a regression statistical model can significantly reduce the variance of residual deviations for cylinders 1–6 (Fig. 4).

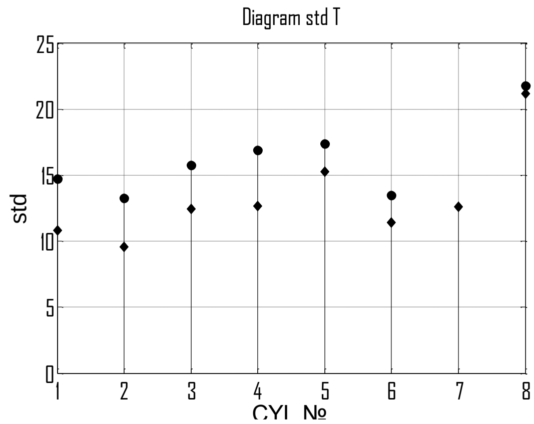

Fig. 4. Change of residual deviations STD with the use of statistical model

D. Calculating the Time Series of DGS Parameters Deviations from Diagnostic Statistical Model

When building the feature space, the temperature deviations for each of DGS cylinders from the statistical model were taken as its elements.

As it follows from the analysis results, the time dependences of temperature deviations from the statistical model for cylinders 7 and 8 also differ significantly from the time dependences of cylinders 1...6… (Fig. 5).

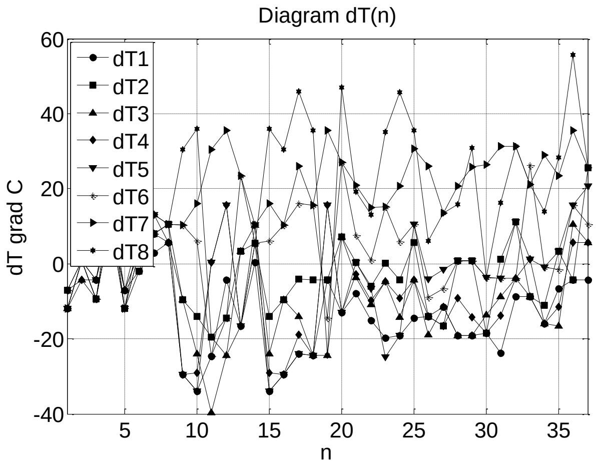

Fig. 5 Time dependences of temperatures deviations from the statistical model:
dT1…dT8 – dependences of temperatures deviations of the exhaust gases of each cylinder from the statistical model

The time series of temperature deviations from the statistical model for cylinders 1...6 have the first two moments constant (mean and variance) and are stationary. In contrast, temperature deviations from the statistical model for cylinders 7 and 8 have a pronounced trend with a positive gradient. Fig. 6 shows such deviations for cylinder 8 together with the linear trend.

The limited size of the analyzed sample does not allow performing an interval assessment of the first, second and mixed moments at a sufficiently high level of statistical significance.

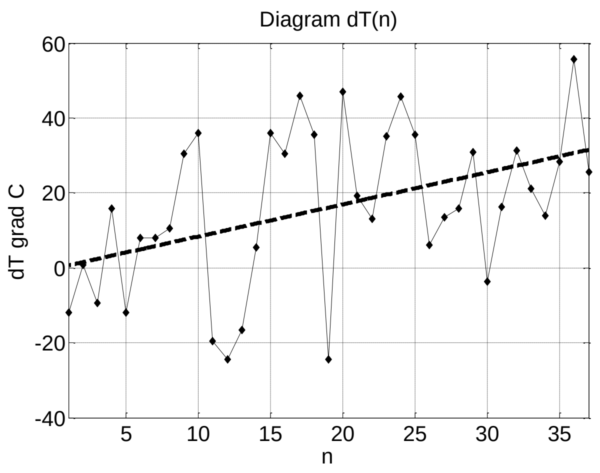

Fig. 6 Dependences of temperature deviations of cylinder 8 exhaust gases together with the linear trend

Linear approximation of the trend component does not permit to obtain sufficient accuracy, namely reduction of residual deviations variance. Therefore, the following approach is proposed to establish the nature of the trend component.

E. Trend Analysis of the Time Series of DGS Parameters Deviations from Diagnostic Statistical Model Based on Singular Matrix Pencil Decomposition

It is known that the decomposition of the time series into components, in particular, into trend, cyclic and noise (interference), is currently a classical problem [7–12, 17].

Various options of singular spectral analysis (SSA), including the well-known Caterpillar method, are based on the principal components method (PCM) in relation to a well-formed feature matrix, the trajectory matrix [17].

The above approaches are based on the known Karhunen-Loeve decomposition and differ only in algorithmic features.

It should be noted that the mentioned methods of svd-expansion of the trajectory matrix of the time series are based on the correlation approach. The singular numbers of the trajectory matrix [18] are the square roots of the eigenvalues of the matrix, proportional to its long-term moving variances. Therefore, the question of the possibility of expanding the known approaches to the analysis of time series based on a priori information is of great interest both for theoretical generalizations and for practical applications. Such a priori information can be based on the fact that the trend of parameters of energy facilities is a natural factor due to their resource exhaustion.

The possibility of using the known approaches to trend analyses of time series of the long operated technical objects data enables the singular value decomposition of a matrix pencil [19], the first of which is the correlation matrix for the generated trajectory one, and the second is the penalty matrix, which takes into account the degradation of characteristics during long-term operation.

As it is known [19], the concepts of singular number and singular decomposition are generalized in [20] for the case of a pair of matrices with the same number of columns. Let A – $m_1 \times n$ matrix and B – $m_2 \times n$ matrix. If the matrix pencil $A^T A - \lambda B^T B$ is nonsingular, that is, the characteristic polynomial $\det\left(A^T A - \lambda B^T B\right)$ is not identically equal to zero by λ, then the finite eigenvalues of the pencil are nonnegative. The arithmetic roots of these are called generalized singular numbers of the pair of matrices $\left(A, B\right)$. In that specific case $B = E_n$ is an identity matrix, we come to the standard *svd*-decomposition of matrix A. If $m_1 > n$, then there exist [17] orthogonal $m_1 \times m_1$ matrix U and $m_2 \times m_2$ matrix V, as well as nondegenerate $n \times n$ matrix S, such that

$$\begin{aligned} &U^T AS = diag\left(\alpha_i\right), V^T AS = diag\left(\beta_j\right), \\ &i = 1, n; \\ &j = \min\left(m_2, n\right). \end{aligned} \tag{1}$$

The relations (1) are called the generalized singular decomposition of a pair of matrices $\left(A, B\right)$. Usually the relations α_i / β_i are called singular numbers of this pair.

In the problems of trend analysis [14, 16, 17], the trajectory matrix X has a dimension $k \times \left(n-k\right)$, where n is the time series sample length and k is the analysis lag. Therefore, the matrix pencil looks as follows:

$$X^T - \left(n-k\right) \times k \quad \text{matrix, } k < n,$$

$$B^T \quad - m_2 \times k \quad \text{matrix.}$$

Accordingly, the characteristic polynomial is transformed to the form

$$D\left(\lambda\right) = \det\left(XX^T - \lambda BB^T\right).$$

The eigenvalues of the pencil are determined by the solution of the equation

$$D\left(\lambda\right) = \det\left(XX^T - \lambda BB^T\right) = 0. \tag{2}$$

Since

$$\begin{aligned} D\left(\lambda\right) &= \det\left(XX^T - \lambda BB^T\right) = \\ &= \det\left(BB^T\right)^{-1} \times \det\left(\left(BB^T\right)^{-1} XX^T - \lambda E_n\right) \end{aligned}$$

and BB^T is a nondegenerate matrix, then the eigenvalues of the pencil are none other than the eigenvalues of the modified correlation matrix $\left(BB^T\right)^{-1} XX^T$.

Let us consider a nondegenerate linear transformation of the trajectory matrix $X_t = TX$. The corresponding correlation matrix has the form $TXX^T T^T$. Its characteristic polynomial can be represented as follows:

$$D(\lambda) = \det\left(TXX^T T^T - \lambda E_n\right) = \\ = \det T \times \det\left(XX^T - \lambda\left(T^T T\right)^{-1}\right) \times \det T^T. \quad (3)$$

By matching (2) and (3), it can be established that T is a square $k \times k$ matrix, and if $T = B^{-1}$, then the matrix pencils (2) and (3) coincide. Consequently, *svd*-decomposition of the matrix pencil is equivalent to the usual singular decomposition of the transformed trajectory matrix $X_t = TX$, which allows the use of proven trend analysis algorithms [14, 16, 17].

Fig. 7 shows the result of the proposed method of trend analysis of temperature deviations in the cylinders of the analyzed DGS.

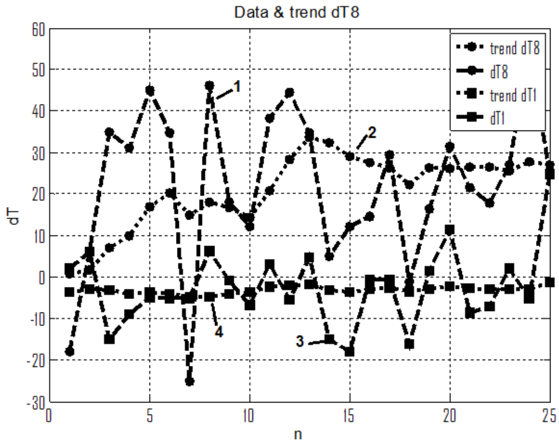

Fig. 7. Dependences of temperatures deviations for cylinders 1 and 8 together with trends
1 – exhaust gas temperatures deviations of cylinder № 8; 2 – deviation trend of exhaust gas temperature deviations of cylinder № 8;
3 – exhaust gas temperature deviations of cylinder № 1; 4 – deviation trend of exhaust gas temperature deviations of cylinder № 1.

F. Diagnostic Message Formation

There is a non-nominal functioning of DGS. The operation of cylinders 7 and 8 of DGS shall be subject to instrumental analysis.

IV. CONCLUSIONS AND RECOMMENDATIONS

The preliminary analysis of temperature modes of marine diesel generator sets allowed expanding the feature space for the subsequent assessment of their technical condition and forecasting. The temperature mode of DGS is an important factor for assessing the possibility of continuing operation according to the technical condition [21]. Based on the analysis of time series of gas temperature deviations from the regression diagnostic model, it is possible to propose a diagnostic message about the non-nominal functioning of cylinders 7 and 8 of the diesel generator under study.

The prospects for further research consist in improving the methods of trend control and analysis of multidimensional time series of ship's DGS technical condition recorded parameters taking into account the presence of related trends arising out of long-term operation.

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