Evaluation of the technical condition of locomotives using modern methods and tools

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Abstract. Considering its real technical condition when planning the volume of repair of locomotive equipment is one of the most important bases for reducing the costs of using railways and the cost of transportation. Continuous monitoring of the technical condition of the locomotive in use is carried out using stationary and on-board technical diagnostic tools. The method of small deviations is now widely used in various fields of science. It is a method designed to determine the existence of a correlation between the changes in parameters describing a process or a physical phenomenon. The method is based on the fact that some of the parameters of the process, in their not so large deviations from their initial values, the relationship between these deviations can be adequately expressed using certain differential calculus ratios. The wide-band exhaust gases oxygen content sensor can continuously monitor the air excess coefficient in the locomotive diesel engine cylinders. This type of sensor is widely used in automotive diesel engine control systems. It means the indirect estimation of the engine cylinders mixture quality by the exhaust gases' oxygen content

1 Introduction

Increasing the efficiency and reliability of locomotives requires regular control of their equipment during operation. With the introduction of modern on-board automation and monitoring microprocessor systems, not only the implementation of emergency alarm when the equipment is in the critical operation mode, but also the effective methods of processing the obtained measurement information, which ensure reliable forecasting of the change in the technical condition of the main units of the equipment, determine their residual resources the issue of development is of urgent importance. The coefficient of air excess is one of the key parameters of the working process in the internal combustion engine, in many respects defining indicators of its reliability and profitability in operation. Values of several other indicators of the working process of the engine are directly connected with the size of coefficient of excess of air, first of all, temperatures of the fulfilled gases (FG). Compliance of relative changes of values of coefficient of excess of air and temperature of the fulfilled gases is the diagnostic parameter characterizing the technical condition of cylinders of the engine [1]. The continuous increase in the level of speeding up of diesels in

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modern locomotives at simultaneous toughening of requirements to their ecological indicators causes the need for improvement of the quality of management of the power plant of a locomotive in transitional operating modes. The use of coefficient air excess as an integrated indicator of the current quality of the working process in diesel cylinders is an essential reserve of improvement in the quality of transients of diesels.

In railway transport, fuel apparatus and cylinder-piston group failures account for 20% of the total number of diesel locomotive failures in operation. This type of failure is one of the causes of excess fuel consumption, and it also allows for determining the scope and frequency of diesel maintenance.

Currently, stationary diagnostic methods are used to assess the technical condition of fuel apparatus and cylinder-piston group, which require a certain amount of time to perform preparatory operations (installation of boilers, connecting sensors, calibrating channels, etc.); these methods are used to reduce failures they are not used continuously, as it eliminates the possibility of determining changes in the technical condition of diesel units and recording them in planning the number of repairs.

Scheduled inspection of diesel equipment without recording the actual condition of diesel equipment leads to excessive consumption of maintenance equipment and an increase in the frequency of equipment failure.

The issue of continuous monitoring of the technical condition of fuel apparatus and cylinder-piston group and other diesel units can be effectively solved by using on-board diagnostic methods, but such methods have been held for a long time by their low level of suitability for locomotive control.

2 Methods

The method of small deviations is one of the methods of linearizing the relationships that describe a certain phenomenon and can be used to simplify and analyze complex systems of equations. Several important issues in the field of engine construction have been successfully solved using the described method. For example, A. Ya. Church was used to calculate the working process of aviation turbojet engines. S.I. Pogodin and D.A. Portnov used the small deviation method to match the power and fuel consumption of high-speed diesels to standard weather conditions. V.I. In Nebesnov's scientific works, it was successfully used for calculation of work procedures during the use of heat power devices when the atmospheric air temperature changes. Although the authors were limited to researching only the effects of temperature and ambient pressure, these scientific works were based on a scientifically based consideration of the effect of external conditions on engine performance.

The range of problems that can be solved using the method of small deviations becomes much narrower as the development of computing techniques and numerical methods of solving nonlinear algebraic and differential equations progress. However, today it can still be effectively used in cases where it is required to determine the nature of the relationship between some parameters of complex processes.

The method of small deviations allows the calculation of relative changes in diesel performance indicators. In such an approach to solving the problem, certain uncertainties in determining the initial values are not of serious importance. Therefore, although the method of small deviations is approximate, the calculation results using it are more accurate than the indicators obtained using detailed calculations of absolute values.

To evaluate the technical condition of the locomotive based on this method, it is necessary to determine not the absolute values of indicators such as temperature, pressure, and fuel consumption but direct changes in the process parameters, that is, their deviations from the initial, known values. Calculating the deviations of indicators allows for a much

simpler solution to the issues under consideration.

3 Results and Discussion

A rationally built methodology for calculating the deviations of indicators greatly simplifies the solution of the considered type of problems. Let the values of y, z, x, t, which consist of certain parameters of the diesel operating condition, be connected with each other using a functional relationship:

$$y = y(z, x, t). \quad (1)$$

(1) we differentiate both parts of the inequality

$$dy = \frac{\partial y(z,x,t)}{\partial z} dz + \frac{\partial y(x,y,t)}{\partial x} dx + \frac{\partial y(z,x,t)}{\partial t} dt \qquad (2)$$

Calculating specific $\frac{\partial y}{\partial z}, \frac{\partial y}{\partial x}, \frac{\partial y}{\partial t}$derivatives concerning initial z_0, x_0, t_0 values of z, x, t variables, and dy, dz, dx, dt differentials can be considered equal to the final increments of parameters y, z, x, t $\Delta y, \Delta z, \Delta x, \Delta t$. In this case, we get the following from the ratio (2):

$$\Delta y = \frac{\partial y(z_0,x_0,t_0)}{\partial z} \Delta z + \frac{\partial y(x_0,y_0,t_0)}{\partial x} \Delta x + \frac{\partial y(z_0,x_0,t_0)}{\partial t} \Delta t \qquad (3)$$

The result of comparing the expression (3) with the Taylor series [1] of the function (1):

$$\Delta y = \Delta z \frac{\partial y(z_0,x_0,t_0)}{\partial z} + \Delta x \frac{\partial y(x_0,y_0,t_0)}{\partial x} + \Delta t \frac{\partial y(z_0,x_0,t_0)}{\partial t} + \frac{1}{1 \cdot 2} \left[\Delta z^2 \frac{\partial^2 y(z_0,x_0,t_0)}{\partial z^2} + \Delta x^2 \frac{\partial y^2(x_0,y_0,t_0)}{\partial x^2} + \Delta t^2 \frac{\partial y^2(z_0,x_0,t_0)}{\partial t^2} + 2\Delta z \cdot \Delta x \frac{\partial y^2(x_0,y_0,t_0)}{\partial z \, \partial x} + 2\Delta z \cdot \Delta x \frac{\partial y^2(z_0,x_0,t_0)}{\partial x \, \partial t} + 2\Delta t \cdot \Delta z \frac{\partial^2 y(z_0,x_0,t_0)}{\partial t \, \partial z} \right] + \cdots \quad (4)$$

If in equation (4) we do not consider the values of the second and relatively higher order small values, we get the expression (3). We present expression (3) in the following variations in relative gains:

$$\frac{\Delta y}{y_0} = \frac{\partial y(z_0,x_0,t_0)}{\partial z} \frac{z_0}{y_0} + \frac{\partial y(x_0,y_0,t_0)}{\partial x} \frac{x_0}{y_0} \frac{\Delta x}{x_0} + \frac{\partial y(z_0,x_0,t_0)}{\partial t} \frac{t_0}{y_0} \frac{\Delta t}{t_0} \qquad (5)$$

By agreeing to record the initial values of variable quantities without 0 indices, we designate, $\frac{\Delta y}{y_0}, \frac{\Delta z}{z_0}, \frac{\Delta x}{x_0}, \frac{\Delta t}{t_0}$ relative gains as $\delta y, \delta z, \delta x, \delta t$. In this case, equation (3) looks like this:

$$\delta y = K_z \, \delta z + K_x \, \delta x + K_t \, \delta t \quad (6)$$

herein $K_z = \frac{\partial y}{\partial z} \cdot \frac{z}{t}$,$K_x = \frac{\partial y}{\partial z} \cdot \frac{x}{y}$, $K_t = \frac{\partial y}{\partial t} \cdot \frac{t}{y}$ is effect coefficients, that is, constants in the considered subrange of variables.

The thermodynamic method is implemented in the mathematical model, in which the cavity of the piston engine cylinder, its inlet, and outlet system conduits and receivers are considered as an open thermodynamic system in which the composition of the working gas mixture changes continuously in the combustion and gas exchange systems, as well as in the compression and expansion processes will be released. It is assumed that the working

gas mixture is in an ideal-gas state. The processes of compression, combustion, and expansion are described without considering the leakage of gas through the gaps between the piston and the cylinder.

The system of equations of the first law of thermodynamics in differential form is used as the initial equation [2,3,4]:

$$dQ_T + dQ_W = dU + pdV. \quad (7)$$

herein: pdV is elemental mechanical work of gas, Dj;

p is cylinder pressure, Pa;

V is cylinder volume, m3;

dQ_T, dQ_W are respectively, the amount of elemental heat brought to the working body when the fuel burns in the cylinder and due to heat exchange with the walls, J;

dU is Changes in elements of the internal energy of the working body, J.

Element change in the internal energy of the working body is determined by the following expression [5]:

$$dU = G \cdot C_V \cdot dT + C_V \cdot T \cdot dG + G \cdot T \cdot dC_V. \quad (8)$$

$C_V = a + b \cdot T$ is isochoric heat capacity of gas taken as a linear function of temperature T, Dj/(kg·ºK);

G is the amount of the working body in the cylinder, kg;

dG is elemental change of the amount of gas in the cylinder due to gas exchange, kg.

External heat input to the system [5]:

$$dQ = \sum K \cdot F \cdot (T_C - T) + i \cdot dG + H_U \cdot d_{g_s}. \quad (9)$$

K is coefficient of heat transfer between gas and objects, j/m2·s·grad;

F is surface of heat exchange with the walls (of the bottom of the sleeve and piston), m2;

Tc is cylinder, and combustion chamber walls (cylinder, piston) gas temperature, ºK;

$\sum K \cdot F \cdot (T - T_C)$ is element amount of heat brought to the working body as a result of heat exchange between the walls of the gas cylinder and the, J;

$i \cdot dG$ is elemental gas heat entering (leaving) the cylinder, J;

i is gas enthalpy in cylinder or collector, J/kg;

$H_U \cdot dg_s$ is element amount of heat introduced by burning fuel in the cylinder, J;

$g_Ц$ is cyclic transmission of fuel, kg.

(9) the summation symbol in the formula takes into account the heat transfer coefficients of the piston sleeve and bottom.

Elements of the equilibrium energy equation for the engine cylinder provided that the gases in the cylinder are completely mixed [5]:

$$dQ_T + dQ_W + i_k \cdot dG_K - id \cdot dG_{K3} - i \cdot dG_B + i_T \cdot dG_{B3} = c_v \cdot G \cdot dt + U \cdot dG + pdV. \quad (10)$$

hereindG_K ,dG_{K3} is the amount of elements of gas entering the cylinder from the collector and from the cylinder to the collector ($P_K > P$)) (gases out, $P_K > P$)) kg;

dG_B, dG_{B3} is the amount of elements of the gas coming from the cylinder to the exhaust collector (P>P_T) and from the collector to the cylinder (gas discharge, P_T>P), kg;

dG_T is the amount of fuel delivered to the cylinder, kg;

i, i_K, i_T is gas enthalpy of cylinder, input and output collectors, J/kg.

Here, the left side consists of the sum of heat energy delivered to the working body due to fuel combustion, heat, and gas exchange. We do not consider the physical heat carried by the sprayed liquid fuel. The first two terms on the right side represent the change in the internal energy of the working body due to the change in the temperature dT and the amount of the working body dG.

Material balance equation for a cylinder [5]:

$$dG = d \cdot G_K - d \cdot G_{K3} - d \cdot G_B + d \cdot G_{B3} + d \cdot G_T. \qquad (11)$$

Equations of ideal gases should be added to equations (10) and (11).:

$$PV = GRT \qquad (12)$$

herein R is the gas constant, J/(kmol·K).

In these equations, it is unknown. If we express the value of the last seven unknown differentials as a function of the crankshaft rotation angle φ, then together with equations (10 — 12), we will have a system of differential equations. This system can be solved using the Runge-Kutt[6] method, which is a numerical method.

Depending on the angle of rotation of the crankshaft, some components are turned to zero in this system of equations to simplify the system. For example, in the case of compression during combustion of fuel and expansion of gases, the equation of material balance will have the following form:

$$dG_K = dG_{K3} = dG_B = dG_{B3} = 0 \qquad (13)$$

As a result of the substitution of the expression from equation (10) and changes (11), we get:

$$dT = \frac{1}{C_V \cdot G}[dQ_T + dQ_W - p \cdot dV + (i_K - u) \cdot dG_K - (i - u) \cdot dG_B + (i_T - u) \cdot dG_{B3} - u \cdot dG_T] \qquad (14)$$

For diagnostic purposes, it is convenient to consider the mixture of gases in the cylinder and exhaust manifold as a mixture of "pure" derivatives of combustion and air, where the proportion of the first in the mixture is equal to r:

$$r = \frac{G_{\Gamma s}}{G_{Bs} + G_{\Gamma s}} \qquad (15)$$

In this case, we determine the values for gas mixtures depending on the temperature T by the methods described above. It is necessary to clarify at what temperature the element values i_K and i_T are calculated. If before the air enters the cylinder (G_K), gases are thrown from the cylinder into the intake collector (G_{K3}) then, the gases thrown into the collector first enter the cylinder. This descent continues until the current G_K value is greater than G_{K3}. Then the average enthalpy of the released gases is equal to:

$$i_K = \frac{\int i dG_{Kz}}{G_{Kz}} \qquad (16)$$

herein i is the enthalpy of gases in the cylinder at the current temperature of the working

body T, J/kg.

Integration is carried out at the angle of rotation of the crankshaft, during which the gases are sprayed. Therefore, it is necessary to calculate $i_K$if it is, then otherwise, when the air temperature in the collector is T_K.

The influence of air on its enthalpy when it moves through the air inlets can be calculated by calculating $T_K + \Delta t$ temperature, where Δt is the heating value (Δt≈10÷15°C).

If the gases are released from the cylinder to the collector (G_B) before the gases fall from the exhaust collector to the cylinder (G_{K3}), then accordingly:

$$i_T = \frac{\int i dG_B}{G_B} \qquad (17)$$

Solving differential equations requires initial values of the variables. Their values depend on the point in the process where the calculation starts. For example, suppose the calculation starts from the closing moment of the input device. In that case, the initial values of P, T, G can be given arbitrarily and compared with the values obtained by the same angle φ at the end of the work cycle. As an initial approximation (approximation) of the values of pressure and temperature at the beginning of compression, it can be calculated according to the accepted calculation methods of the working process, and the amount of the working body can be calculated from the equation of state. When calculating the periodic functions r, T, G, their initial values should correspond to their final values. If the specified accuracy is not observed, then the calculation should be performed with new initial values. It is possible to give these quantities within the permissible limits by successive approximations.

The combustion process of the fuel in the cylinder will look like this. Elemental heat release during fuel combustion in a diesel cylinder cannot be determined by rigorous theoretical calculations. For this reason, researchers use various empirical and semi-empirical correlations. The heat release depending on the angle of rotation of the crankshaft can be expressed by an exponential relationship:

$$dQ_T = g_s \cdot H_U \cdot \frac{\varphi - \varphi_\Gamma}{\varphi_C^2} \cdot \exp\left(-\frac{\varphi - \varphi_\Gamma}{\varphi_C}\right) d\varphi. \qquad (18)$$

where φ_T is the angle at which heat starts to be released, gr. p.k.v.;

$\Delta\varphi = \varphi - \varphi_T$ is the angle corresponding to the transfer of fuel in the cylinder, gr. p.k.v.;

H_U is lower specific heat of combustion of diesel fuel, J/kg;

g_s is cycle transfer of fuel, kg;

φ_C is parameter determined based on experience, gr. p.k.v.

4 Conclusion

To determine the rate of heat release at the end of fuel combustion, it is proposed to determine the indicators in several stages, which include the delivery and spraying of fuel into the cylinder, the parameters of the charge of the working body, the physicochemical characteristics of the fuel and its evaporation characteristics in the combustion chamber, the kinetics of chain reactions of the heterogeneous fuel-air mixture. Descriptions are taken into account. However, most of these parameters can be found only by the experimental method, which excludes the possibility of using this approach to solve this problem.

The start of combustion is determined by calculating the ignition duration from the moment of fuel injection. A.I. Tolstov's formula is widely used to determine the fuel

ignition delay duration, and its empirical coefficients can be used in tests of high-speed engines with direct fuel injection.

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