Technical State Monitoring of Automatic Control Systems

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Abstract. The article substantiates the need for technical monitoring of automatic control systems and suggests a method for supervising their technical state based on the example of speed controllers in internal combustion engines. The causes of occurrence and negative impact of irregular rotation rate on the efficiency of power plant use are described. The main diagnostic parameter characterizing the regulation quality should be the behavior of the automatic control system in a dynamic transient process when a single multistage disturbing effect enters the system input. As such an effect, it is proposed to use crankshaft angular acceleration during internal combustion engine free acceleration. The results of theoretical and experimental studies confirming the validity of selected engineering solutions are presented. It is proved that maximum crankshaft angular acceleration negative value in the oscillatory transient during completion of engine free acceleration depends on the degree of speed controller non-uniformity, which determines the deterioration rate of its parts and the state of the adjustment parameters. The significance of regression equation coefficients, which describe the obtained interdependence, is confirmed, and a device for monitoring technical state of automatic speed control systems is developed. The proposed method of supervising the technical state of speed controllers ensures the implementation of remote technical monitoring and contributes to improving operation efficiency of transport vehicles and technological equipment.

Keywords: Automatic regulation · Technical monitoring · Power plant · Transient process · Angular acceleration

1 Introduction

In for power plants in vehicles and technological equipment; their operating modes are usually characterized as unsteady. When combined with cyclical operation typical for many power plant types, inertia forces of unbalanced masses and a number of other reasons, irregular driver shaft rotation occurs, which requires the presence of automatic speed control systems. At the same time, in order to ensure operation efficiency of

A. Manakov and A. Edigarian (Eds.): TransSiberia 2021, LNNS 403, pp. 265–273, 2022.
https://doi.org/10.1007/978-3-030-96383-5_30

power plants, it is necessary to optimize the parameters of control systems, as there is a discrepancy in the time of the necessary rotation speed change and magnitude changes in the resistance moment as well as other reasons that cause irregular rotation. As a result, the insensitivity zone presence leads to deterioration in the performance of the machines [1]. any industry or transport sector, there is a need to use automatic control and management systems; their continuous improvement occurs due to the complication of functional circuits and the use of modern electronic components and microprocessor devices. To ensure their operability control during operation, it is necessary to develop methods for performance quality control of these systems. This is especially important.

For example, operation processes of ship power plants are characterized by the occurrence of irregular propeller drive shaft rotation in oscillation conditions due to the propeller movement into and out of water. Then regardless of weather conditions, it is necessary to ensure vessel controllability by providing steady operation of the main engines [2]. Similar problems arise in agrotechnical and road-construction work, as well as in locomotive power plant operation, where the resistance to movement or relocation of operating devices is constantly changing. Incomplete use of the potential power plant power with variable external load nature is also typical for electric generator sets, as in this case, ensuring the speed control quality is extremely important for providing the constancy of given alternating current frequency value [3]. Recently, the issues of rotation speed stability of internal combustion engines when using promising types of alternative fuels have been relevant and attracting the attention of scientists [4–6]. Therefore, the improvement of design and operational parameters of power plants without providing effective and reliable methods of speed control quality check is impossible.

High-quality rotation speed control is also required in metal-working processes, since due to intermittent nature of material and tool cutting and damping, uneven allowance and irregular rotation of the drive mechanisms, fluctuations of various frequencies and amplitudes occur in processing equipment drive, reducing the accuracy and surface quality of the manufactured parts.

The change in speed control parameters of various mechanical systems and, in particular, internal combustion engines, leads to an inevitable change in the technical state of speed controllers during operation. Regulator defects have a significant impact on the parameters of irregular rotation and transient quality, which leads to increased fuel consumption and reduced machine use efficiency. Reasons for failures of power plant speed regulators can be: increased friction, mechanical damage and fatigue destruction of parts, wear of regulator parts, changes in the stiffness of elastic elements, defects of electrical elements and control circuits. Despite the obvious optimization of technical state monitoring frequency and the development of operational methods for technical diagnostics of automatic speed control systems, insufficient attention is currently paid to this issue [7].

The purpose of this study is theoretical operational control methodology justification of speed controller technical state according to transient parameters (based on the example of diesel internal combustion engines) and experimental proof of theoretical prerequisite accuracy.

2 Research Methods

The solution to problems of technical monitoring process implementation of automatic speed control systems can be based on both methods of continuous and discrete technical state monitoring of the regulators. The optimal monitoring frequency, which minimizes machine maintenance and operation costs, can also be achieved by organizing discrete monitoring, for example, on the basis of a risk-oriented approach [8]. Therefore, when developing methods and means of technical monitoring of automatic regulation and control systems, it is necessary to consider the experience in development and application of such devices designed for railway rolling stock and providing information transmission via mobile or satellite communication [9, 10].

In this regard, when developing methods and tools for technical monitoring of regulatory systems, it is necessary to consider the possibility of rapid transmission of diagnostic information through communication lines and media networks. It should be taken into account that the control quality in electronic control systems is largely determined by the size of the sampling interval and depends on the accuracy of restoring the original analog signal at the specific moment [1].

Existing methods of monitoring speed controller technical state are most often based on the use of adjustment and static regulator parameters. The behavior of an automatic control system in a dynamic transient process during a single multistage disturbing effect appearance should be considered the main quality indication of system functioning. The prospects of using dynamic parameters that determine the nature of transient processes in automatic speed control systems are undeniable, but they are not widely applied in operational diagnostics due to a number of reasons. One of them is the lack of research and complexity of the transient control process parameter dependencies from regulating equipment technical state. Moreover, the regulations for maintenance of rolling stock and technological equipment do not contain sufficient information about the required characteristics of transients or other parameters that characterize the technical state of automatic control systems. Existing methods of transient parameter registration usually include the presence of external load change simulators.

It is proposed to use free acceleration transients in order to develop methods of technical diagnostics of internal combustion engine speed regulators. In this case, the engine is loaded by its own inertia forces, and the acceleration intensity, determined by crankshaft angular acceleration, is a characteristic of its power. Engine free acceleration eliminates the need to use special equipment which ensures the creation of transients that simulate the modes of resetting or increasing the load. The analysis of speed control system transients allowed us to assume that during regulator technical condition assessment under operating conditions, it is preferable to use angular crankshaft acceleration at the final stage of engine free acceleration instead of rotation speed (angular velocity). In contrast to similar rotation speed oscillations, crankshaft angular acceleration oscillations are characterized by a significant amplitude peak relative to the zero value with zero transient and a sign change. Thus, the quality information content of transient process, described as interdependence of angular acceleration and time, implies the convenience of the proposed instrumental processing. As a specific variable of the diagnostic parameter, it is proposed to use the maximum value of the negative angular acceleration quantity, achieved in the first semi-oscillation which occurs along with completion of the engine free acceleration process (Fig. 1).

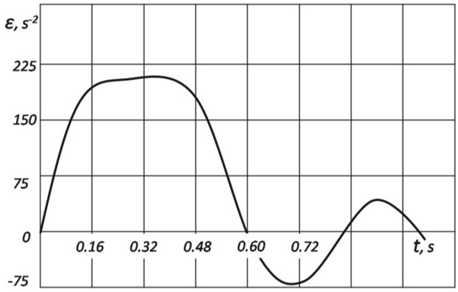

Fig. 1. The nature of the internal combustion engine free acceleration transient process.

Mathematical model of the automatic control system during engine free acceleration process is a system of equations describing joint engine and regulator movement:

$$\begin{cases} T_d \frac{d\phi}{dt} + \gamma\phi = \psi - f(t) \\ T_r \frac{d^2\eta}{dt^2} + T_k \frac{d\eta}{dt} + \delta_r \eta = -\phi \end{cases} \tag{1}$$

where φ – the relative change of the crankshaft angular velocity in dimensionless units; T_d – time constant of the engine; ψ – the relative position of the fuel supply management unit (control rack); γ – the coefficient of engine self-regulation; η – the relative position of the controller executive unit; *f(t)* – engine load relative value variation in time; *Tr* – time constant of the controller; *Tk* – the indicator of friction in the controller; δr – the degree of regulator non-uniformity.

For convenience of performing theoretical calculations, we apply transformation of the equation system (1) to one normalized equation of third order. In the operator form, when using the symbolic operator form of differential equations, where *dx/dt* = *px*, the demonstrated system will be as follows:

$$\begin{cases} (T_\partial p + \gamma)\phi = \psi - f(t) \\ \left(T_p^2 p^2 + T_K p + \delta_p\right)\eta = -\phi \end{cases} \tag{2}$$

Internal combustion engine free acceleration belongs to a unit step transient type, described by the following interdependence:

$$f(t) = \pm k_p \cdot 1(t) \tag{3}$$

where the coefficient kr determines reduction degree or, conversely, load increase, and the multiplier 1.(t) shows that for $t < 0\, f(t) = 0$.

Thus we obtain a normalized characteristic equation of the following form, in which the coefficients a and b determine structural static parameters and technical condition parameters of the engine and regulator:

$$\left(a_0 p^3 + a_1 p^2 + a_2 p + a_3\right) L[\phi(t)] = \pm \frac{k_p}{p}\left(b_0 p^2 + b_1 p + b_2\right) \tag{4}$$

Let us simplify the resulting formula (to reduce the text volume, a significant part of transformations is not presented in this article) and determine engine crankshaft angular acceleration as a time derivative of relative angular velocity:

$$\overline{\varepsilon}(t) = Ce^{-\alpha t}[\alpha \sin(\beta t - K) + \beta \cos(\beta t - K)] \tag{5}$$

Equation (4) is an approximate mathematical description of the relative change in diesel crankshaft angular acceleration during free acceleration, in which K is a constant associated with the magnitude of the regulator non-uniformity degree, and the coefficients α and β are, respectively, the real and the imaginary part coefficients of the simplified characteristic equation roots (6):

$$a_1 p^2 + a_2 p + a_3 = 0 \tag{6}$$

Next, it is necessary to estimate the amplitude values of the angular acceleration in the damping oscillatory process. To find the moments of time corresponding to the extreme values of the relative angular acceleration, the following expression is defined:

$$t_э = \frac{1}{\beta}[arctg\frac{2\alpha\beta}{\alpha^2 - \beta^2} + K + \pi n] \tag{7}$$

In the expression (7), maximum values of angular acceleration in damping oscillatory process correspond to even values n = 0, 2, 4, and minimum values correspond to equivalent odd values of semi-oscillation ordinal number, for example:

$$t_1 = \frac{1}{\beta}[arctg\frac{2\alpha\beta}{\alpha^2 - \beta^2} + K + \pi] \tag{8}$$

$$t_3 = \frac{1}{\beta}[arctg\frac{2\alpha\beta}{\alpha^2 - \beta^2} + K + 3\pi] \tag{9}$$

Extreme values of the angular acceleration in the transient free acceleration are determined by the expression:

$$\overline{\varepsilon} = Ce^{-\frac{\alpha}{\beta}[arctg\frac{2\alpha\beta}{\alpha^2-\beta^2}+K+\pi n]} \cdot \left\{\alpha \sin[arctg\frac{2\alpha\beta}{\alpha^2 - \beta^2} + \pi n] - \beta \cos[arctg\frac{2\alpha\beta}{\alpha^2 - \beta^2} + \pi n]\right\} \tag{10}$$

Thus, knowing automatic control system static parameters, it is possible to determine semi-oscillation amplitudes, as well as the duration of the transient process. Since the coefficients of the above equations characterize, among other things, the technical condition of the speed controllers, prerequisites are created for technical state diagnostic technology development for speed controllers in internal combustion engines under operating conditions according to the parameters of free acceleration transients.

3 Study Results

To assess the quality of the automatic control systems and controller technical state, a limited set of dynamic characteristics is sufficient. Bound characteristics of the transient process can be used as an example: the value of the second angular acceleration semi-oscillation of engine crankshaft free acceleration (i.e. the extreme value of the first negative angular acceleration semi-oscillation) and the damping oscillation time. Instead of transient process total time, it is possible to use its components, namely the duration of individual semi-oscillations. Let us set known static characteristic nominal values of the A-41 diesel engine (Td = 1.59 s, Tr = 0.0186 s, δr = 0.07) and perform the corresponding calculations. The regulator non-uniformity degree is an important characteristic of the regulator technical state and features relative change in the adjustable rotation speed during static load change from zero to the nominal value. Degree values can vary widely under different operating conditions. As a result of the calculations, we obtain the dependence of the maximum negative angular acceleration, expressed in relative units (Fig. 2).

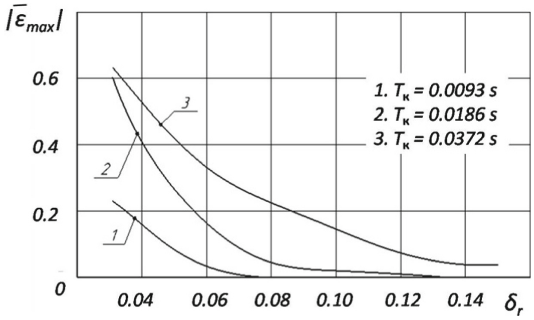

Fig. 2. Theoretical interdependence of the maximum angular acceleration negative value on the regulator friction coefficient and the degree of regulator non-uniformity indicated in relative units.

Experimental studies were conducted to prove the obtained theoretical interdependencies. The study of the malfunction influence on the nature of transients in the automatic control system was carried out by modeling gaps in an exhausted regulator. The change in total gap size in transmission mechanism for regulator control actions to the diesel fuel pump significantly changes the nature of transients (Fig. 3). The absolute values of engine free acceleration do not change significantly, but the total duration of the transient process, semi-oscillation duration and crankshaft angular acceleration amplitude oscillation values change.

The obtained interdependences of the angular acceleration semi-oscillation duration τ on the value of the control rack free stroke show that the duration of the transient process as a whole, as well as its specific sections is impractical to use as a diagnostic parameter, since this value is characterized by low information content and mathematical description complexity of experimental data (Fig. 4). When the grease level changes and, accordingly, the regulator dry friction level increases, the value of the selected diagnostic parameter also changes slightly.

Thus, the maximum negative value of crankshaft angular acceleration in the oscillatory transient process during completion of engine free acceleration was finally chosen as the response. This parameter can also be called the first negative semi-oscillation of angular acceleration under the disturbing influence of the unit-step type (engine free acceleration). The selected diagnostic parameter is correlated with the speed controller

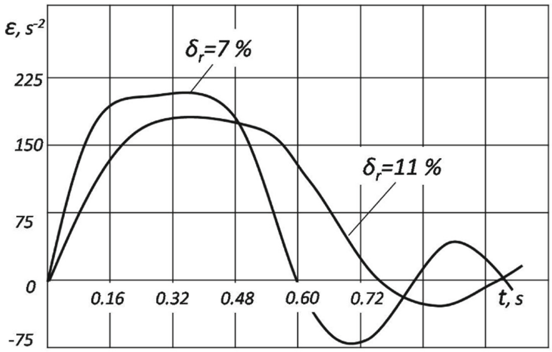

Fig. 3. An example of the speed controller technical state influence on the engine free acceleration transient process parameters.

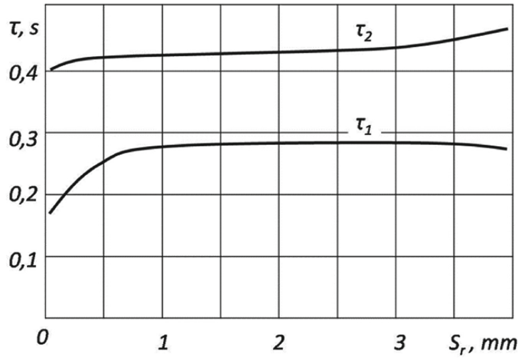

Fig. 4. Dependences of the first and second semi-oscillation duration. Regulations from total gap setting in the rack control assembly.

static parameter – the degree of non-uniformity which determines the wear degree of parts and adjustment violations. As a result of experimental data processing, a regression equation was obtained and the significance of its coefficients was confirmed (Fig. 5):

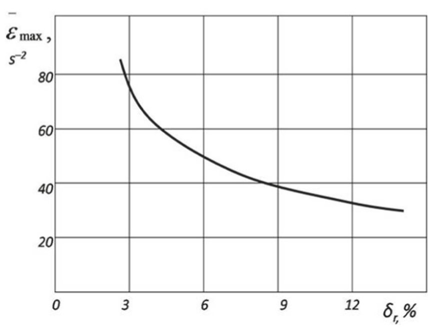

Fig. 5. The nature of the regression dependence of the maximum engine angular acceleration negative value on the regulator non-uniformity degree.

Based on the obtained research results, a technology for evaluating the technical state of speed controllers has been developed and tested. To implement the proposed diagnostic technology, a device for monitoring the technical state of automatic speed control systems has been developed and tested. This device allows us to measure rotation speed instability during steady engine operation, and to measure the maximum angular velocity and acceleration values, as well as transient process duration with a sharp increase or decrease in the load. Digital processing of diagnostic information allows us to use monitoring results for the organization of vehicle technical state remote monitoring.

4 Discussion of the Results

Theoretical and experimental studies have confirmed the validity of using the dependence of engine free acceleration transient parameters on regulator technical state in order to ensure operational supervision of automatic speed control systems. The connection of speed controller technical state to the transient parameters in automatic speed control systems is established. It is proved that the most informative transient indicator is the amplitude value of the first negative angular acceleration semi-oscillation of the engine crankshaft during diesel engine free acceleration. Regression dependencies were obtained experimentally, confirming the validity of the proposed theoretical assumptions.

The proposed methodology for assessing the technical state of automatic speed control systems in operational conditions will increase the efficiency of using transport vehicles and technological equipment. The method of assessing speed controller technical state using dynamic parameters of repetitive transients can be applied not only to mechanical systems of power plants, but also to a wider range of control systems for various purposes and operational principles.

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