Injection Engine as a Control Object.

II. Problems of Automatic Control of the Engine

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Abstract—Specific features of injection engine as a control object are discussed, strict formulations of problems of engine automatic control and principles of their solution are presented. Examples of solution of the problem of stabilization of air–fuel ratio and engine torque control problems are presented as illustrations for demonstration of application of modern methods of automatic control theory for solution of control problems of injection engines.

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INTRODUCTION

In the first part of the paper, the mathematical model of internal combustion injection engine was presented. In this paper, we consider the main tasks of automatic control of the engine. They are determined by engine operation regimes and properties of the engine as the control object. Therefore, we begin with analysis of these properties.

1. PROPERTIES OF ENGINE AS CONTROL OBJECT

The mathematical model of the internal combustion engine introduced in the first part of the paper (see Eqs. (4.4)–(4.11) can be written in the following generalized form:

\[ \dot{x} = f(x, \theta) + g(x, u, \delta, \theta), \]  
\[ \dot{v} = Av + By(t - \tau), \]  
\[ y = h(x, z, u, \theta), \]  
\[ z = h_2(x, v), \]

where \( x \in \mathbb{R}^2 \) is the state vector of the engine whose elements are the crankshaft revolution angle \( x_1 = \omega \), the mass flow of the fuel film \( x_2 = \mu_f \), and the pressure in the intake manifold \( x_3 = P; u \in \mathbb{R}^3 \) is the vector of control signals including the amount of fuel injected into the cylinder \( u_1 = \mu_f \), the rotation angle of the throttle gate \( u_2 = \alpha \), and the spark angle \( u_3 = \alpha_{ign} \); \( y \in \mathbb{R}^2 \) is the vector of controlled variables including the fuel excess coefficient \( y_1 = \phi \) and the torque \( y_2 = M \); \( v \) is the state vector of the measurement system; \( z \) is the vector of measured signals (i.e., output signals of \( \lambda \) probe, sensor of crankshaft velocity vector, air pressure sensor, sensor of air flow in intake manifold, etc.); \( \theta \) is the vector of unknown parameters; \( \delta \) is the vector of unavailable for measurement external perturbations; \( \tau \) is the transport delay in the measurement loop (first of all typical for \( \lambda \) probe and caused by the time of passage of exhaust gases from the cylinder to the sensitive element of the sensor).

In this system of equations expression (1.1) describes the dynamics of the engine and expression (1.2), the dynamics of measurement devices. It was noted in the first part of the paper that in modern engine control systems as a rule it is impossible to neglect the dynamics and delay in measurement loops, which dictates the requirement of addition of the mathematical model of the engine by models of measurement devices. Equations (1.3) and (1.4) establish the connection (in the general case nonlinear) of state coordinates of the engine and measurement devices with controlled and measured variables.

Thus, in the general case the mathematical model of the internal combustion engine is referred to the class of nonlinear parametrically undefined systems with dynamic measurements, delay, and external perturbations. Moreover, in description of the engine behavior in different regimes, it is necessary to take into account the nonstationary character of engine characteristics (causes, in particular, by engine heating processes).

Note the following important properties of the mathematical model of the internal combustion engine which should be taken into account in synthesis of control algorithms.

(1) Approximate character of mathematical model. Sufficiently complex chemical, thermal, mechanical, and electric processes take place in the internal com-
bustion engine. As a consequence, even most complex engine models (nonlinear, nonstationary, and with delay) are approximate and reflect the engine behavior only with certain degree of accuracy. Moreover, many parameters and characteristics of the engine cannot exactly be calculated analytically, but are established experimentally or should be estimated by the control algorithm in the course of its operation. Therefore, upon construction of mathematical models of injection engines experimental characteristics play a large role [1, 2], and upon synthesis of high accuracy control laws adaptation and self-learning methods are widely used [3–5].

(2) Validity of the model in admissible range of state and control values. For normal operation of the engine and conservation of reliability of the chosen model it is necessary to preserve the values of the states and control signals of the engine in the given range. For example, if the air excess coefficient exceeds some threshold value (i.e., in the case of very lean mixture) the chemical reaction of combustion of the fuel mixture terminates and the presented mathematical model loses physical meaning. Preservation of the air excess coefficient in the admissible range should be provided by the control system. Similarly, the engine rotation rate \( \omega \) (controlled by the driver or special control algorithm) should also be in the bounded range \( 0 < \omega_{\text{min}} < \omega < \omega_{\text{max}} \). The reduction of the velocity below \( \omega_{\text{min}} \) results in the engine shutdown (due to termination of the combustion process), and the growth of the velocity above \( \omega_{\text{max}} \) can result in damaging its elements. In both cases the mathematical model of the engine becomes unreliable. Therefore, keeping state and controlled variables in the working ranges is one of the main tasks of the automatic control system.

(3) Nonlinearity of dynamics and control. Even simplified models of the engine and its basic subsystems are nonlinear (see formulas (4.1)–(4.11) in the first part of the paper). Therefore, the construction of control laws based on linearized models (that was typical for one of the first stages of development of automatic control systems for engines) does not provide sufficiently accurate solutions. All modern engine control algorithms are nonlinear.

(4) The internal stability and boundedness of states for bounded input. In spite of essential nonlinearity of the mathematical model the engine, due to the specific features of chemical, thermal, and mechanical processes taking place in it, in the working range of its state values it represents stable system, and in the case of constant input actions the state variables and controlled quantities tend to constant bounded values.

(5) Parametric uncertainty. The presence of unknown parameters in the mathematical model of the engine is caused by several factors. First, even a strongly simplified and idealized model of the engine includes the description of the dynamic process characterized by fundamental parametric uncertainty. Namely, the process of deposition of the fuel film on the walls of the intake manifold (see Eq. (3.10) in the first part of the paper) in the first approximation is expressed by aperiodic first order link for which the numerical values of the time constant \( T \) and the transmission coefficient \( K \) cannot be measured or analytically calculated. Second, the parametric uncertainty of the model is determined by approximations of a number of nonlinear static characteristics of the engine whose coefficients cannot be exactly calculated a priori. Third, the technological spread of engine parameters, change of its operation regimes, and wear of engine elements result in the parametric uncertainty. Even in the assumption that for this engine model complete identification of its model has been performed in plant conditions, in the course of its operation the parameter values vary and for two identical cars these changes become different with time. Oscillations of parameter values can be fast (caused, for example, by the engine heating) and slow (wear and aging of units). These factors result in the requirement of application of algorithms of estimation of engine parameters in the course of operation and require methods of the theory of adaptive and self-learning systems in controller synthesis [6–12].

(6) Presence of external perturbations. Part of perturbations acting on the engine as the control object are available for measurement (such as ambient air temperature), while other perturbations (external load on the engine shaft depending, in particular, on the character and inclination angle of the roadbed, or the quality of the fuel mixture supplied to the injector) cannot be directly measured. The presence and character of these perturbations can be detected by the engine behavior which dictates the necessity of application of methods of estimation and compensation of external perturbations [7–13].

(7) Dynamics of measurement devices. Measurement devices of modern engine automatic control systems introduce noticeable amplitude and phase distortions into the spectrum of useful signal, which is caused by the dynamics and nonlinearity of these devices. For example, model of \( \lambda \) probe produced in the 1980–1990s, possessed static characteristics close to the relay one. As a rule, upon synthesis of closed-loop automatic control systems for engines, it is impossible to neglect the dynamics and/or nonlinearity of measurement devices, which results in the necessity of compensation of these distortions based on algorithms of identification or observation [14–18].

(8) Delay in measurement channel. Measurement of air excess coefficient directly in engine cylinders is impossible due to high temperatures and pressure. Therefore the \( \lambda \) probe is installed in the exhaust manifold. The time required for the exhaust mixture to reach the sensor determines the delay in the measurement channel. This time is not constant—it is inverse proportional to the engine rotation rate and decreases at high rotation rate. Thus, one of the main feedbacks