Using experience of the dynamic models of piston internal combustion engines

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Abstract. This article describes using experience of the hierarchical system of dynamic models for researching the operation and calculation of piston engines. The results of practical using and the possibilities of dynamic models developed by the authors are shown.

1. Introduction

The modern stage of theoretical investigations of reciprocating internal combustion engines (ICE) is characterized by the great variety of the applied mathematical models which complexity constantly increases. Mathematical simulation as the research instrument in the modern theory of reciprocating engines occupies an important place and promotes their progress development. Evolution of ICE simulation is developing now in a direction of more and more detailed account of assemblage of various factors, raises of an exactitude and giving to models of natural properties.

The complete analysis of papers has shown that it is paid more and more attention to the problems of the engine construction «as a whole system» because of computing machinery development and considerable advances in the field of ICE simulation. The whole system engine models as a whole system are the mathematical models reflecting process of engine functioning in time as a uniform system.

This paper sets the classification of models and the comparative analysis of the mathematical models applied to researches of functioning and calculation of ICE as a whole system. Dynamic models as the most perspective are observed more detailed. The results of ICE calculations which were got by the dynamical models developed by authors are shown. The results of the research project are published with the financial support of Tula State University within the framework of the scientific project № 2017-22.

2. Types of the mathematical models applied to ice mathematical description «as a whole»

Currently according to the character features it is possible to merge the models of ICE «as a whole», which applied to ICE functioning researches and calculation, in the following four types: thermodynamic, mechanical, informational, dynamical.

The thermodynamic models [1-3] are the most wide-spread and represent the mathematical models of ICE working processes. The basic set of equations is the equations (1) of working fluid mass and
energy balances added with relationships for calculation of a heat capacity of working fluid, heat exchange, gas exchange, fuel delivery, mixing, combustion and emission of harmful substances in this case are used:

\[
\begin{align*}
\frac{dm}{dt} &= \sum_{j=1}^{k} G_{nj} - \sum_{j=1}^{k} G_{pj}, \\
\frac{dU}{dt} &= \sum_{j=1}^{k} G_{nj} + \sum_{j=1}^{k} G_{pj} + Q - p\frac{dW}{dt},
\end{align*}
\]

where \( G_{nj} \) and \( G_{pj} \) – input and output mass flux density through a j valve bore respectively; \( Q \) – heat release (or removal); \( i \) – specific enthalpy of working fluid.

The observed models, as a rule, describe only an intracyclic exchanges of engine working processes parameters with high confidence. Mode of ICE behavior in this case is set by values of crankshaft speed and cyclic fuel delivery (excess air ratio).

Mechanical models [4-6] are founded on the system dynamic equation «the engine – a user»:

\[
\frac{d\omega}{dt} = \frac{M_\omega - M_\epsilon}{J_\omega},
\]

where \( M_\omega = M_j - M_a \); \( M_a \) – the moment of mechanical losses; \( M_j \) – the indicated engine torque.

The indicated mean torque of the engine is defined in observed models by means of functional dependences of a view:

\[
M_\epsilon = f(\omega, p, h, \eta_i); M_j = f(\eta_i); M_a = f(p_j); M_\omega = f(\omega),
\]

Where \( p \) – pressure of charging air; \( h \) – a position of controls fuel delivery; \( p_j \) – an indicated mean pressure; \( \eta_i \) – indicated efficiency.

The mechanical models allow to gain relationship at various laws of a loading, however they demand considerable quantity of experimental data on the engine, so it restricts their application.

The information models [7, 8] are founded on the automatic control theory. In this case the mathematical identification of ICE elements by the standard links used in the theory of automatic control takes place. Every element is observed as a controlled process having input and output magnitudes link between them is presented by differential equations of a view [8]:

\[
T^2 \frac{d^2 A_i}{dt^2} + T_1 \frac{dA_i}{dt} + A_{i0} = K_i \Delta M_\epsilon,
\]

where \( A_i \) – observable ICE parameter; \( A_{i0} \) – initial value of observable ICE parameter; \( T_\theta \) – factors of differential equations; \( K_i \) – coefficients of amplification; \( \Delta M_\epsilon \) – the law of a resist torque variation operating on a engine crankshaft. Behavior of the engine in various modes of regimes is analyzed by means of linear differential equations (3) and a superposition principle.

The observed models are applied to perfecting of engines automatic control systems. As a deficiency of information models it is important to note necessity of experimental definition of factors of differential equations.

The dynamic ICE models are divided into two types: quasidynamic and actually dynamic models.

The feature of quasidynamic models [9, 10] is joint application for the describing of the engine operation of the set of equations engaging the equations (1) and (2). Thus the average engine torque is
defined from an indicator diagram gained by calculations. In this case engine operation is observed as the process consisting of a consecutive row of work cycles different from each other, identical to corresponding cycles of steady-state behavior. Application of the quasidynamic models is linked with assumption about existence of a resistant to steady-state behavior of operation of the engine during separately taken cycle without detection of this fact that distorts dynamic properties of the engine. Thus calculation of angular velocity variation is carried on a large grid with a step equivalent to cycle time.

Thermodynamic, mechanical, information and quasi-dynamic models according to the classification presented in the work [11], are usually «mean value models».

Actually the dynamic models or «event based models» [12-17] are deprived noted deficiencies as describe engine operation as taking into account intracyclic, and an intercyclic variation of the engine work parameters. In the fundamentals of observed models differential equations (1) and (2) are assumed. Thus the torque instantaneous value in the equation (2), is defined as follows (for the single-cylinder engine):

\[
M_\phi = a_4 \left( (p - p_0) f_n - F_{\phi\phi} - a_3 m_4 \omega^2 - a_2 m_4 \frac{d \omega}{dt} \right),
\]

where \( p_0 \) – gas pressure under the piston; \( F_{\phi\phi} \) – a frictional forces in mechanism; \( m_4 \) – a reduced mass of parts of the engine reciprocating;

\[
a_2 = r_k \left( \sin \phi + \frac{\lambda}{2} \sin 2 \phi \right); \quad a_3 = r_k \left( \cos \phi + \lambda \cos 2 \phi \right),
\]

\[
a_4 = r_k \sin \phi \left[ 1 + \frac{\lambda \cos \phi}{1 - \lambda / 4 \cdot (1 - \cos 2 \phi)} \right]; \quad \lambda = \frac{r_{sp}}{l_w},
\]

where \( r_{sp} \) – crank radius; \( l_w \) – length of a connecting rod.

3. **ICE Dynamic models**

The most perspective models among introduced above are dynamic models for the following reasons:

A. These models at higher level then other models present ICE transient condition as a whole systems because of full account intracyclic and intercyclic parameter changes of the engine operation.

In particular, the calculation result [14] difference of ICE transient condition for dynamic and quasidynamic models in feature determination of fuel-handling system reach 23 %, parameters the inlet and outlet of the systems – 2 %, effective indexes of engine operation – 12 % (figure. 1).

![Figure 1](image-url)

**Figure 1.** Calculation results of angular velocity and torque in transient regime, calculated by dynamic and quasidynamic models.

B. Multicyclic calculation of ICE transient condition is made by these models, the steady state is considered as a special case of the transition. Thus, the models allow in fully to perform calculations both static (figure. 2), and dynamic characteristics (figure. 3) of ICE [14].

C. The models are opened so process models in ICE cylinders and systems may be connected with them [13-15]. According to the results of computational experiments on dynamic models developed
recommendations [15] to improve the efficiency of the diesel TMZ-450D in the composition of the electric unit, in particular:

- rational choice of parameters of the air-gas path and gas exchange system allowed to increase the torque and power of the diesel engine by 7.5 %;
- rational choice of parameters of the automatic speed control system allowed to reduce the slope of the regulatory branch from 5.07 % to 4.80 %, and the transition time – from $\tau = 1.1$ s to $\tau = 0.44$ s

![Figure 2. ICE static characteristics.](image)

![Figure 3. Modification of indexes operating characteristic (indexes) of diesel engine TMZ-450D in transient operating conditions.](image)

For the VAZ-2111 engine, experimentally practical recommendations for the modernization of the intake system were developed and confirmed. At the same time, the inter-cylinder power unevenness and the average indicator pressure at the frequency of 2000 rpm were reduced by 21 %, at the frequency of 5000 rpm by 16 %, the power characteristics of the engine improved by 6-8 %.

The developed dynamic models can be successfully used in the design calculations of the ICE, which is illustrated in [14, 15].

D. The use of dynamic models allows to observe ICE as nonlinear dissipative thermomechanical system [12]. This system is applicable to apparat of nonlinear dynamics. Nonlinear dynamics [18-20] becomes the theoretical base for research of the complete effects inherent ICE, for example:

1) It is possible to exist several ways simultaneously in development of transient processes. Such possibility is caused by the choice of initial and/or boundary conditions; accepted values of model parameters. In the first case a transition to any regime among a large variety of the possible regimes having their own attractive areas is observed. In the second case reconstruction of a large variety of possible regimes and appropriate model solutions can be observed.

The boundary between steady modes of behavior, i.e., equilibrium position ($\omega = 0$) and stable limit cycle was constructed using dynamic model. This boundary was simulated for the same sequence changes regulators (figure. 4). The angular velocity is selected as the initial condition.

2) Bifurcational dependence and dynamic (phase) variables from design parameters of a construction, properties of working mediums, etc. The bifurcation diagram is shown in figure. 5 which divides the range of inertia moment of gyrating ICE details into parts, which determine availability of stable limit cycle and stable equilibrium state ($\omega = 0$). The shown boundary lines are conditions of bifurcation transition: loss of stable limit cycle. This bifurcation is widely observed in the ICE theory and practice in the problem of starting qualities and the problem of the engine cutoff (stability loss) during excess of allowable value by loading moment. The stable ICE operation is arranged above the graph in figure. 5.

3) Existence of complicated stationary regimes which are presented not by unique, repeating from cycle to cycle indicator diagram. These regimes are irregular (chaotic) regimes. At the deeper level bifurcation ICE properties are observed in a known problem of intercyclic nonidentity [21, 22].
shown that intercyclic nonidentity can be observed as outcome of transition to an irregular (chaotic) regime. In particular, the data cited in operations [21, 22] shows dependence of ICE work process type from mixture composition. It should be noted that the ICE dynamic model can show the ability to bifurcations to the irregular (chaotic) regime even in the 0-dimensional form. On figure. 6 the sequence of indicator diagrammes is shown in figure. 6 which correspond to the cycles of period 1, 2, 4, 8, 3, and also the chaotic regime that can be considered as reflecting intercyclic nonidentity.

4) Ability to generation of the ordered (dissipative) structures at the most various levels of the exposition. The observed dynamic models can successfully be applied at projecting calculations of ICE that is illustrated in research work [12].

4. Conclusion
In this paper the perspective application and the further development of ICE dynamic models is shown by the analysis. These models allow to describe engine operation as the whole dynamic system taking into account complex interconnections of its elements. The piston engine as a complex system has
special system properties not inherent to the individual elements. These properties are the result of combining the functions in time and space. Therefore, the property to execute the set objective function is realized only by system as a whole, instead of its separate elements.

Thus, the dynamic models are the effective instrument of optimizing calculations of piston engines on the steady-state and transient conditions.

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