MATHEMATICAL MODELLING OF DIESEL ENGINE TESTING AND
DIAGNOSTIC REGIMES

Lenar A. Galiullin, Rustam A. Valiev
Kazan Federal University, Naberezhnye Chelny Institute

ABSTRACT
They studied the application of the diesel engine mathematical model for the automatic generation of
control vectors by its operating modes during testing. This model is represented as a graph for a more
visual representation. The adequacy of a diesel engine management model is evaluated on the basis of
simulated and experimental characteristics comparison. The merits of the proposed mathematical model of
a diesel engine, in comparison with the methods used previously, can be represented by the greater
versatility of the model, which allowed to take into account almost any number of parameters affecting the
course of tests and engine diagnostics. A representation of the mathematical model of the engine in the
form of a graph was suggested, which made it possible to identify the connections between the elements
of a test bench and external factors. The application of differential equation system and its subsequent
solution made it possible to specify any existing modes of diesel engine operation. The model allows you
to specify the number of parameters that affect the accuracy of control during engine testing and
diagnostics. The error of the proposed model and the method of the diesel engine control management was
estimated by the comparison of transient characteristics of KAMAZ 740.60 obtained experimentally and
imitatively. The control error was 0.076%, which indicates a high accuracy of control.

Keywords: mathematical model, graph, diesel engine, automated engine testing system.

INTRODUCTION
The time spent on internal combustion engine (ICE) design makes 5-10 years often, including the time
spent on experimental testing and engine diagnostics. The debugging process continues during the entire
period of model serial release until production termination [1].

The most promising way of quality improvement, the development time reduction, fine tuning and the
preparation of serial production of ICE is the automation of some engine unit design, in particular, through
the use of automated design systems, as well as the automation of experimental tests and engine studies
based on automated testing and diagnostic systems (ATDS) [2].

The studies of internal combustion engines are labor-intensive and costly (about 80% of the total amount
of work for an engine creation - experimental work). It is also difficult to analyze and process the results
of ICE tests and diagnostics.

The use of automated systems for internal combustion engine testing and diagnostics, as a rule, leads to
the reduction of engine test performance and result analysis in 5-10 times [3].

Therefore, Russian and foreign scientists, as well as machine-building enterprises, pay a lot of attention to
the creation, implementation and operation of ATDS of different engine models.

Most of Russian systems for ICE diagnostics, automation and testing were developed on individual orders,
and each of these systems was almost unique one [4].

A wide use of ATDS at engineering enterprises for different models of modern ICEs and the types of their
testing is impossible without the solution of unified mathematical and software support problem for
automatic preparation and technological algorithm tuning. These difficulties and problems are also
exacerbated by the requirements of function continuous increase performed by a system, and the need for a frequent adaptation of algorithms due to constant changes in technology (in particular, during research and final tests of ICE).

The testing of internal combustion engine is an integral part of the complex process of their creation, improvement and production. This is explained by the fact that it is possible to assess the technical and economic efficiency of the engine designed or modernized, the real loads on the components and the parts of an engine, and also the improvement of serial engine production technology only during testing [5].

the methods of mathematical modeling, the course of the engine working processes and the entire work cycle are analyzed, its main characteristics and indicators are predicted.

process of the work for an automated test and diagnostic system, it is necessary to find the parameters of ICE mathematical model, which is necessary to calculate the control actions for the engines. The specification of engine mathematical model provides an automatic adjustment and the control of an automatic test bench. Besides, control actions can be used to specify the operating modes of engines using computers in the course of bench tests [6,7,8].

As a rule, the mathematical models of engines are given in the form of algebraic, integral, differential equation systems, etc. At the same time, as they already mentioned, a model can not be completely adequate to an object and reflects only some of its properties of interest for the purposes of a particular study.

In this regard, the importance of research, the determination of an engine compliance with technological and general requirements of time, has acquired special significance.

The introduction and the development of automated systems for engine diagnosis and testing are carried out by foreign and domestic enterprises and firms. Their systems are different, at that different measuring and computing equipment are used, and there is also a different functionality.

During the operation of an automated test and diagnostic system at test stations, in particular during research and development, various functional possibilities are often required. Therefore, in these cases it is very desirable to have a modular structure of an automated test and diagnostic system.

**METHODS**

The study uses the model of a supercharged diesel engine in the form of an object controlled by the speed of a crankshaft, which is given by a linear differential equation [9]:

\[
T_2 \frac{d^2 \omega(t)}{dt^2} + T_1 \frac{d\omega(t)}{dt} + T_p \omega(t) = T_h \frac{dh(t)}{dt} + \\
+ K_h h(t) - T_m \frac{dM_C(t)}{dt} - K_m M_C(t)
\]  

(1)

where \( \omega(t) \) - the frequency of a shaft rotation;

\( h(t) \) - the position of a fuel pump rail;

\( M_C(t) \) - the load value;

\( T \) - time;
The constants, depending on engine design features.

This model contains one output value \( \omega(t) \) and two input values: \( h(t) \) and \( M_C(t) \). Taking into account the model (1) and using the representation of the diesel engine control model in the form of a graph, a graphical representation of the model is obtained, as shown on Fig. 1.

Here \( M_C \) - the input variables of the required load and engine rotation speed, \( h \) and \( M_C \) are the parameters determining the position of the fuel injection pump rail and load respectively, and \( \omega \) is the output signal indicating the engine shaft rotation speed [10].

In accordance with the abovementioned graph, the mathematical model of diesel engine control can be written in the form of formula (2) and (3).

\[
\begin{align*}
\frac{dh(t)}{dt} &= T_h \cdot h(t) + K_{hm} \cdot M_C(t) + K_{\omega} \cdot \omega(t) + 0 \cdot M_C \\
\frac{dM_C(t)}{dt} &= 0 \cdot h(t) + T_m \cdot M_C(t) + 0 \cdot \omega(t) + K_c \cdot M_C \\
\omega &= K_h \cdot h(t) + K_m \cdot M_C(t)
\end{align*}
\]

RESULTS AND DISCUSSION

Using the method of a diesel model representation in the form of a graph, it is possible to represent the control of a diesel engine in the form of graphic images (Fig. 2).
Fig. 2. Graphical representation of the diesel engine control model in the form of a graph
Here $U(t) = (U_1(t), U_2(t), \ldots, U_p(t))^T$ - the vector of the model input parameters, $Y(t) = (Y_1(t), Y_2(t), \ldots, Y_z(t))^T$ - the vector of the model output parameters, $X(t) = (X_1(t), X_2(t), \ldots, X_m(t))^T$ - the vector of variable states.

The input parameter vector $U(t)$ determines the following control operations: the control of the shaft rotation speed, the control of a loading device, oil condition, fuel condition, coolant temperature control, the modeling of the engine operating conditions (for example, weather simulation), etc. [11]

The output vector $Y(t)$ determines the supported motor parameters, for example, engine shaft rotation speed, fuel consumption, the level of smoke, etc.

The state change vector $X(t)$ determines the operation of an engine and control devices, such as the high pressure fuel pump rail, brake unit, etc. [12]

This graph, depending on the quality requirements to the created mathematical model, allows you to link the variables of the model, setting the weight coefficients on the arcs of the graph with different values [13].

**CONCLUSIONS**

In order to verify the adequacy of the model obtained earlier to set the test modes for a diesel engine, the diesel engine control model, represented in the form of formula (2) and (3), is used for simulation modeling using "SciLab" package. To do this, we need to obtain a vector transfer function $W(p)$, which can be derived from the following formula:

$$W(p) = C \cdot (p \cdot E - A)^{-1} \cdot B$$

(4)

Here $A$, $B$, $C$ are the matrices and the vector, obtained from the coefficients of the formula (2) and (3). In this case, $A = \begin{pmatrix} T_h & K_{hm} \\ 0 & T_m \end{pmatrix}$, $B = \begin{pmatrix} K_{w} & 0 \\ 0 & K_c \end{pmatrix}$, $C = \begin{pmatrix} K_h & K_m \end{pmatrix}$.

Substituting the values $A$, $B$, $C$ into the formula (4), we obtain a vector transfer function, which will look like this:

$$W(p) = \left( \frac{K_h \cdot K_w}{p - T_h} \frac{K_h \cdot K_{hm} \cdot K_c + K_m \cdot K_c \cdot (p - T_h)}{(p - T_h) \cdot (p - T_m)} \right) =$$

$$= \left( \frac{K_h \cdot K_w}{p - T_h} \frac{K_h \cdot K_{hm} \cdot K_c + K_m \cdot K_c \cdot (p - T_h)}{p^2 - (T_h + T_m) \cdot p + T_h \cdot T_m} \right)$$

(5)

In order to obtain the coefficients, the obtained model, they use the parameters of KAMAZ engine 740.60 are used. Thus, the coefficients will take the following values: $K_{hm} = -0.005; T_m = 0.933; K_m = 0.68; K_w = 0.008; K_h = 120; T_h = -3.333; K_c = -1.32.$

At that the vector transfer function (5) takes the following form:

$$W(p) = \left( \frac{1}{1 + 0.3 \cdot p} \frac{-2.16 - 0.9 \cdot p}{3.2 + 2.4 \cdot p + p^2} \right)$$

(6)
In the process of testing KAMAZ 740.60 engine, the data was obtained in accordance with the international standard 1585 in stationary modes at KI-15711-01 stand and used to develop the characteristics of one of diesel engine testing stages.

Measures and records were performed using the automated equipment for the collection and the processing of incoming data of the following parameters: the torque and the speed of a crankshaft.

The experimental unit for the tests consists of a studied object - the internal combustion engine and the automated system.

Experimental studies of the engine with nonstationary loading were carried out according to the following procedure [14, 15]:

1) at the engine load, one needs to wait for 20 minutes at least until \( \omega \) and \( M_C \) are permanent, and only then measurements were made;

2) the maximum braking resistor moment during the experiments was selected in such a way that the rotation of the engine crankshaft did not decrease below 2200 rpm under load, since the engine starts to work with some overload;

3) After experimental studies, they obtained the characteristic of diesel engine operation, formed for the regimes when \( M_C = \text{var} \) and \( h = \text{const} = \text{max} \) (load increase).

This graph (Fig.3) characterizes an engine operation in the mode of load-increase. It can be seen that after the engine heating, the load is fed to the shaft, the engine speed decreases, and after about four seconds a diesel engine starts to work in a steady state. During the tests, the maximum load makes \( M_C = 244.12 \text{ Nm} \).
Fig. 3. Step response of the diesel engine (1 - modeled, 2 - experimental)

This combination of characteristics gives an idea about the simulation accuracy. Obviously, in the most remote areas of the graph, the simulation error with respect to the rotational speed of the motor shaft was 10 rpm.

In order to test the adequacy of the model, the least squares method was used. The simulation error was determined by the comparison of the experimental transient response and the simulated response. The error was 0.076%.

SUMMARY
The advantages of the proposed mathematical model in comparison with previously accepted decisions include its greater versatility, which allows to take into account any number of factors affecting the test system.

The representation of the model in the form of a graph easily reveals the connection between the elements of a test stand and external factors. The solution of the system of differential equations will allow to
describe any existing modes of diesel engine operation. The number of considered factors determines the accuracy, which allows a researcher to control the quality of the tests.

The check of obtained model error was performed by the comparison of the transient characteristics of KAMAZ 740.60 engine and the transient characteristics derived from its mathematical model. The obtained error was 0.076%, which indicates the adequacy of the model.

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