Experimental and analytical methods for determination of Internal combustion engine parcial velocity characteristics

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Abstract. The article reviews the existing methods for determining the mechanical map of internal combustion engines, namely the dependence of the torque on the engine speed at different levels of fuel supply. Experimental and computational methods are considered. The main advantages and disadvantages of the methods considered are listed.

Currently, the vast majority of modern cars are equipped with internal combustion engines (ICE), mainly of two types – gasoline and diesel. It is the internal combustion engine that largely determines the operational properties of the car (traction-speed, fuel efficiency, the amount of harmful substances emissions).

In addition, modern ideas about the nature of the car movement in real conditions, based on the probabilistic idea of the roads longitudinal macro-profile parameters, the distribution of speeds on different gears within the route on the road with a certain type of longitudinal macro-profile, allow early in the design to determine the possible average speed on different routes, the optimal speed for the fuel efficiency criterion, maximum speed and other equally significant performance indicators.

The choice of internal combustion engines for a particular car model and the subsequent optimization of the transmission ratios in order to obtain optimal characteristic signs of some performance properties are based on the study of certain parameters and characteristics of the internal combustion engine.

One of the most important characteristics of the engine is its mechanical map, namely the dependence of the torque on the engine speed at different fuel feed levels. A feature of this characteristic of the engine is the ability to perform further analytical studies to determine the performance properties of the car, based on the use of "partial" characteristics of the internal combustion engine defined in this work as the torque dependence, power and some other parameters on the crankshaft speed with limited fuel supply at a certain level.

The most traditional tool for obtaining a mechanical map in the experimental studies process is a dynamometer test bench for testing the engine. So, for example, in work [1] the technique of the mechanical map construction with application of the dynamometer for the engine tests is presented. On the basis of the data obtained, the engine parameters are calibrated and optimized to achieve improved fuel efficiency while meeting the requirements for harmful substances emissions. With the undoubted advantages of this method, the results of the experiment can be influenced by the peculiarities of the experimental cycles.
In some cases, in order to obtain the necessary characteristics other, rather complex methods of experimental studies can be used. For example, in work [2] in order to determine the parameters of the ICE mechanical map, a test bench with classes dynamometer on which the car is installed (motor transport system, MTS) is used. This method makes it possible to obtain the actual parameters in the process of testing. Testing MTS driven by its own engine with a significant design simplification of the test bench requires the support of a computer system for processing the results. The paper notes that when performing dynamic tests (under sharp loading by additional dynamic moment) partial characteristics are distorted. Distortion of the characteristics is also possible in static tests, also carried out using brake mechanisms with a braking torque fixation of at least five seconds. In this case, work [2] proposes a method for calculating the external and partial characteristics of the engine, based on the use of experimentally obtained values of the maximum power and the corresponding maximum power of the engine crankshaft speed. The paper proposes a method for calculating these characteristics, based on an arbitrary gradation of partial regimes. Steps of gradation are taken in the range of $0.3 \leq r \leq 1$, $r=1$ corresponding to the external high-speed characteristic, and the rate of partial characteristics is defined by the expression

$$r = \frac{n_N - n_r}{n_N - n_c} = \frac{N_r}{N_{max}}$$

(1)

where $n_N$, $n_r$ respectively, the crankshaft speed of the engine at maximum power ($r=1$) and at maximum power for partial mode ($r<1$), $n_c$ is engine speed at idle.

The next step is to determine the maximum idle speed. In this case, a number of assumptions concerning the input coefficients linearity of the maximum idle speed correction are allowed. As a result, the values of these coefficients are taken tentatively, and subsequently refined by the results of the actual measurements obtained during the test. The power dependence $N(n,r)$ in the mode of the engine operation on the partial characteristics and in the range $n_p \leq n \leq n_r$ is based on the known Leiderman formula. To calculate the power characteristic $N(n,r)$ on the site $n_p \leq n \leq n_{Ns}$ in the analyzed work, we propose a Leiderman – Hodes formula similar to the Leiderman formula, but allowing to adjust the coefficients $C_1$ and $C_2$ by additionally introduced coefficients taking into account the following parameters.

$$\frac{n - n_r}{n_r - n_c}$$

(2)

As a result, it is proposed in accordance with the expression

$$M = 9554 \frac{N}{n}$$

(3)

To calculate the parameters of the partial characteristics, specifying them in the process of additional bench tests. The complexity and ambiguity of the calculation results of partial characteristics in this case is obvious. The method described in this paper also implies certain analytical calculations.

In work [3] the technique of experimental determination of the engine mechanical map parameters at the movement of the car on the mixed cycle is given. For this purpose, vehicle on-Board diagnostics (OBD) is used.

For the methods specified in works [1] and [2], it is necessary to have a special dynamometer test bench. In addition, the methods specified in works [2] and [3] require the engine to be installed in an existing vehicle. In many cases, when designing, the possibility of installation of several constructive engines variants on the vehicle and the choice of the optimal criteria for object design are in the works. Thus, the use of experimental methods for determining the parameters of the ICE mechanical map despite the significant material costs is a necessary procedure.

A significant advantage of experimental methods is the reliability of the results. Among the drawbacks, it should be noted that in all three of the above methods, the presence of the object of study is necessary for research. Moreover, to achieve the reliability of the results, it is necessary to
conduct tests for a sample consisting of several engines. In this case, the bigger the sample size, the higher the reliability of the results. That is, the reliability of the test results should be ensured by increasing their volume and cost. Another feature of the results is the significant nonlinearity of the experimental characteristics. In many cases, the use of engine characteristics as a data set is limited by certain considerations. In these cases, known techniques can be used to adjust the experimental characteristics (approximation methods).

In addition to experimental and experimental and analytical methods, which involve a fairly complex and costly process of obtaining the necessary characteristics, there are currently analytical methods for constructing partial characteristics. Their complexity and costs associated with their implementation are small, so the development of analytical calculation methods of ICE specified characteristics is appropriate.

In work [4] the mathematical description of experimentally obtained partial speed characteristics of the engine by means of the interpolation Lagrange polynomial of the second and third orders providing high accuracy of results is offered. Fuel supply modes from 50% to 100% in this case are described by a second order polynomial, less than 50% of the third order, Fig.1. It is noted that the method of perturbation formation in the study of dynamic processes in the car transmission, namely the determination of the effective torque value is of great importance.

![Figure 1](image)

**Figure 1.** Partial velocity characteristics of the engine with 50% fuel feed: a – polynomial of the 3rd degree, b – polynomial of the 2nd degree

In work [5] a method of determining the partial velocity characteristics of engines using multi-dimensional interpolation, leading to the construction of the surface $T_e(\omega_e, \beta)$, where $\omega_e$ is the crankshaft revolutions, $\beta$ is the level of fuel passing through the array of points that describes the surface in the coordinates $(T_e, \omega_e, \beta)$ is proposed. The surface is created by areas of two-dimensional splines, which are functions $(\omega_e, \beta)$, and having continuous first derivatives at both coordinates. This, according to the authors, allows you to accurately determine the value of the effective torque at all fuel feed levels and the angular velocity of the crankshaft.

For greater clarity, the spline surface can be represented as a model of an elastic plate of infinite length deformable by bending. To build the surface shown in figure. 2, quite complex expressions of
smoothness functionals, expressions for the spline function in partial derivatives are written and the values of the coefficients $c_i$ and $C_N$ for the equation (4) are determined from the system of linear expressions, which is an approximation polynomial of the ICE partial characteristics.

$$T_e(\omega_e, \beta) = \sum_{i=1}^{N} c_i r_i^2 \ln r_i^2 + C_{N+1} + C_{N+2} \omega_e + C_{N+3} \beta$$  (4)

where $r_i^2 = (\omega_e - \omega_i^2) + (\beta - \beta_i)^2$, where $T_e$ is the current value of the engine torque, $C$ is approximating coefficients, $\omega_e$ is revolutions of the crankshaft corresponding to a current torque value, $\omega_i$ is crankshaft speed corresponding to the torque values of the partial characteristic curve points from 1 to N, $\beta$ is the level of fuel feed corresponding to the current value of the torque, $\beta_i$ is the level of fuel corresponding to the torque curve of the partial features from 1 to N.

Splines interpolation allows you to simplify the process of numerical integration. According to the experimental data obtained, the function is interpolated and a functional dependence is constructed describing the surface corresponding to different values of the effective torque of the engine, depending on the fuel supply level and the crankshaft speed, Figure 2.

![Figure 2](image_url) **Figure 2** Partial velocity characteristics of the engine

![Figure 3](image_url) **Figure 3** Experimental and calculated partial characteristics of the engine: a-experimental, b-calculated
It is noted that the obtained approximation of the partial velocity characteristics of the ICE coincides quite accurately with the experimentally obtained dependences, Fig. 3.

In work [6] a search for the nominal values of the partial torque characteristics of the engine according to the following formula is proposed:

$$M_{e.H,i} = M_{e.H} \frac{n_{X,i} - n_{H}}{n_{X} - n_{H}}$$  \hspace{1cm} (5)

where $M_{e.H,i}$ is effective nominal torque of the partial characteristics of the engine, $M_{e.H}$ is nominal effective torque external speed characteristics of the engine, $n_{X}$ is maximum speed of the motor shaft rotation, $n_{X,i}$ is maximum frequency of the motor shaft rotation at partial characteristics, $n_{H}$ is rated engine speed.

The definition of intermediate torque values of partial characteristics is proposed to perform in accordance with the expression

$$M_{e.i}(n) = M_{e.H,i} \left(\frac{n_{X,i} - n}{n_{X,i} - n_{H}}\right)$$  \hspace{1cm} (6)

where $M_{e.i}(n)$ is the intermediate torque of the ICE partial characteristics, $n$ is the engine speed corresponding to the intermediate torque.

It is obvious that the considered method [6] involves scaling the curve of the external speed engine characteristic and the use of the torque change curve character in the construction of partial characteristics.

In modern ICEs with electronic control fuel feed the partial torque characteristics have a rather complicated analytically difficult to predict form. At a different fuel supply level, the curve nature of the torque from the engine speed varies in a complicated way. A view of the real partial characteristics of the modern diesel ICE is shown in Fig. 4. Therefore, in the analytical determination of the modern ICE mechanical map parameters, the approximation of curves by polynomials of the third order or their scaling with a high probability will not allow to obtain a reliable result.

**Figure 4** Partial characteristics of modern diesel engine at 40%, 60% and 80% fuel feed level

As a result of partial speed characteristics modeling methods research it is established that the existing methods can be divided into experimental (research) and computational and experimental. In the first case, the speed characteristics are based on the test results of the engine on the test bench, and then approximated using known methods. In the second, during the laboratory experiment, the values
of several points of the external velocity characteristic are determined, according to which partial characteristics are built in accordance with some analytical dependence.

Analytical methods for constructing partial characteristics in many cases require the determination of coefficients with uncertain physical meaning, which makes their use quite difficult in engineering calculations. In addition, the experimental determination of several points of the external velocity characteristics requires a full preparation of the experiment, and the impossibility of obtaining partial characteristics in the required amount is likely to be due to the technical features of the test bench and equipment.

The most optimal way to obtain partial characteristics, in the opinion of this paper, is an actual full-scale experiment. In this case, the most difficult point is the approximation of the obtained characteristics by the method that provides the use of approximating dependencies for solving some specific problems of the car dynamics study.

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References
[1] Barker T D 1982 Engine mapping techniques Vehicle design 2 (3) 142 - 152
[2] Hodes I V, Bazhin O A, Shelukhin S V 2010 Calculation and experimental determination of the external and partial characteristics of the engine during the test on the test bench with the drive of the motor transport system Vestnik of SibADI 30-32
[3] Bishop J at. al. 2016 Engine of fuel use and emissions from transient driving cycles 183 202-217
[4] Lukin P P and Solomatkin N S 1985 To harmonic analysis of partial speed characteristics of carburetor engine Collection of scientific papers MAMI: Reliability and active safety of the car. – Moscow 270-282
[5] Solomatin N C, Zamorin A G and Zotov E M 2010 Approximation of partial speed characteristics of an internal combustion engine Izvestiya MSTU "MAMI" 1 66-72
[6] Boyarkina I V 2011 Methods of analytical calculation of partial speed characteristics of torque and hourly fuel consumption of internal combustion engines Oriented fundamental and applied research as the basis of modernization and innovative development of architectural, construction and road transport complexes of Russia. All-Russian scientific and technical conference (with international participation). -Omsk: (SibADI) 481-485