Dynamic tests in real vehicle conditions

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Abstract. The report is devoted to the problem of building feedback with the car during its operation. It analyzes the problems that require feedback from the vehicle, clarifies the reasons why insufficient attention is paid to this issue, and discusses methods for obtaining the most informative data at the lowest cost. When working on the report, the authors relied on the results of their professional activities, which consists in the development and application in practice of diagnostic techniques for automobile internal combustion engines. The least costly and technically easy to implement is getting data from the engine management system controller. To increase the information content of such data, it is required to organize their correct processing and cataloging. You can get information about the progress of the working process in the engine cylinders by means of indication - direct or indirect. The implementation of direct indication is laborious and costly, therefore, with the help of direct indication, the authors of the report develop an indirect indication method based on the analysis of changes in the instantaneous crankshaft speed obtained as a result of processing the signal from the crankshaft position sensor. A promising complex of feedback with a car during operation should receive most of the data on engine operation from the ECM, but to calculate the generated torque, the complex must register a signal from the crankshaft position sensor using an ADC.

1. Introduction

When creating an engine and its control system, the conditions under which it will be operated are usually known [9, 10, 11]. Next, the prototype engine is installed on the engine stand and with the help of an engineering control unit, all its characteristics are checked for compliance with the specified ones. Then, as part of the car, the engine goes to road tests, during which, hung with a lot of additional sensors, it is checked in conditions as close as possible to real operational conditions. At the same time, based on the results of test tries, some changes are made to both the design and the management program. One of the tasks of such test trips is to develop a self – diagnosis system-how the control system should respond and how it reacts to the occurrence of malfunctions.

After that, the car moves to another stage of its life cycle. At this stage, most modern ECM as feedback, there is only a warning light when the malfunction occurs. Further tightening of environmental standards, together with the need to improve fuel efficiency [5] and the use of alternative fuels [6, 7, 8], creates the prerequisites for improving the methods of feedback with the car during its operation.
2. Tasks of getting "feedback" from the car in the vehicle's operating conditions.

Is there any confidence that in a car, which, on the one hand, is a complex technological product, and on the other, is a mass-produced product, made, moreover, in a short time, the workflow is optimally managed? And if any malfunction occurs, then how adequately will the self-diagnosis system work in this case? The self-diagnosis system of the car in general and the engine in particular is best suited to deal with obvious malfunctions - wire breaks or sensor values outside the set limits. In this case, the self-diagnostic messages are quite specific and on their basis it is easy to localize the malfunction that has occurred. In the case of more complex malfunctions - a violation of the mutual consistency of the sensor readings, that is, their signals go beyond the mathematical model - the developers of engine control systems offer various test blocks to help localize the malfunction. In the event of a malfunction, the accompanying information is also recorded - the driving mode, readings of some sensors and control parameters. But the greatest influence on the speed and correctness of diagnostic actions depends on the competence of the diagnostic engineer performing these actions. To date, there is no comprehensive approach that allows you to get full feedback from the car during its operation. There are several reasons for this:

- The technical ability to receive data from the ECM controller, as well as the controller itself, as an integral part of control systems, appeared less than 30 years ago.
- "Development" and "operation" refer to different periods of the vehicle's life cycle, so it is not economically feasible to transfer the "feedback" methods used during development and Debugging to the period of operation.
- For widespread use of "feedback" techniques, there must be an appropriate level of technical personnel accompanying the vehicle during operation.

The automotive industry is developing very dynamically and what seemed to be a fantasy, such as self-driving cars, is now considered a not so distant prospect. In this regard, the methods of obtaining a stable "feedback" with the car during operation are becoming more and more relevant.

Let's look at what tasks this is relevant for:

- A set of tasks related to traffic management, traffic mode, and route planning. At the same time, the vehicle speed and dynamics of its changes (vehicle acceleration), engine operating mode (crankshaft speed and generated torque), as well as geolocation data are relevant for analysis.
- Clarification of vehicle and engine operating modes, analysis of the operation of the control system in these modes, as well as analysis of changes in the characteristics of the engine and control system components over time. This "feedback" is relevant for car manufacturers, as well as analytical centers of the "Car – Environment – Road" type.
- Monitoring the condition of cars of individual customers (subscribers) of service centers or the fleet of their own cars. This control allows you to detect and even predict the onset of failure of some elements of the engine and control system, as well as speed up the localization of the fault in the event of combined failures.
- Control of the vehicle operation in case of changes in the control program, as well as when the vehicle is operated in modes other than the calculated ones.

3. Analysis of the available opportunities for obtaining "feedback" with the vehicle in the vehicle operating conditions.

Information that can be obtained from the car as a "feedback" should be divided into two groups:

3.1. Information received from the ECM controller via the digital data exchange bus.

Today, the vast majority of cars produced have a standardized connector for connecting diagnostic equipment, through which you can also register-write to a file - some parameters of engine operation in real time. The trend in the global automotive industry is to expand the ability to access information received from the ECM - increasing the number of available parameters with the placement of these
data on servers available to interested parties.

Receiving data from the ECM controller requires minimal technical costs, but a significant
disadvantage of such data is its "subjectivity". In the case of various violations, the sensor signals are
distorted, and the assessment of the operating mode and the control actions are determined incorrectly
by the controller. This is especially important when determining the torque generated by the engine.
The controller performs its calculation using a mathematical model based on sensor signals.

3.2. Information received via channels independent of the ECM controller. This information can be
obtained from additional sensors placed on the engine, or as a result of independent signal
processing of standard sensors.

Placing additional sensors on the car is very expensive and can only be justified if there are specific
research tasks, or when conducting in-depth diagnostics in case of complex malfunctions.

Information about the flow of the working process in the engine cylinders is the most important
information and diagnostic parameter, but directly obtaining it - indexing – is very expensive and time
– consuming. Therefore, indication under operating conditions is rarely used. Various methods of
indirect indexing are an alternative to direct indexing. The crankshaft senses the torques generated as a
result of working processes in all cylinders of the engine, its angular velocity and acceleration depend
on the nature of their flow. When developing methods for indirect indexing, it is necessary to take into
account all the factors that affect the parameters of the crankshaft rotation and identify the influence of
the working process against their background.

When conducting a number of research works and in-depth diagnostics, the noise and vibration of
the power unit may also be of interest. Appropriate sensors are used to study them. If you process the
signals of these sensors together with the signal of the crankshaft position sensor, then noise and
vibration can be synchronized with the processes in the internal combustion engine.

4. Practical implementation of "feedback" with the car during operation.

More than 15 years ago, the development of a diagnostic complex (DC) for internal combustion
engines began in the Problem Laboratory of Transport Engines of Moscow Automobile and Road
Construction State Technical University. Interim results of work with practical examples of the use of
diagnostic complex in vehicle diagnostics were reported at IASF 2007. The first version of the
complex was based on a 16-channel ADC installed in the PCI slot of the PC, that is, it was stationary.

In the process of using the complex - diagnosing vehicles with complex malfunctions and carrying
out research work - ideas for its further development appeared, and a list of tasks for the solution of
which the use of the complex would be relevant.

It became clear that the complex must be mobile to solve many problems. Therefore, a mobile
version of the diagnostic complex was created several years ago.

The number of sensors and actuators in a modern automobile engine has multiplied, therefore, in
the mobile version of the complex, the number of simultaneously recorded data lines has increased.

To obtain information on the progress of the working process in our laboratory, a miniature
pressure sensor was developed, for which a patent was obtained in 2018. Figure 1 shows: a - sensor
design, b - sensor integrated into the spark plug.
Figure 1. a - design of a miniature pressure sensor, b - pressure sensor combined with spark plug.

Now it is possible to carry out test trips on a car with a connected diagnostic complex, including indication of the internal combustion engine in road conditions. Now the ICE diagnostic complex is used when carrying out various studies of engine operation as part of a vehicle - Fig. 2.

Figure 2. A car with a connected diagnostic system.

A good correlation between the torque generated by the engine and the acceleration of the crankshaft has been known for a long time and is evident - Fig. 3, but to calculate the torque based on the change in the angular speed of the crankshaft, an indirect indication technique is required. Now we are working on such a technique using direct indexing data; more will be said about this later.
5. **Processing data received from the ECM.**

Receiving data from the ECM through the diagnostic connector is the simplest, from the point of view of technical implementation, way of obtaining "feedback" from the car. These data, even if they are analyzed without data of direct or indirect indexing, can be quite informative, while the way of their processing and systematization is of decisive importance. Depending on the research tasks, the data obtained from the ECM controller, it is advisable to analyze using various methods:

- As a function of time. For such an analysis, fragments of a relatively short duration - tens of seconds and a pronounced causal relationship - are suitable - when an event entails a change in the parameters of work - Fig. 4.

**Figure 3.** A fragment of the engine operation at the moment of a sharp change in the generated torque.
In the function of the operating mode. For this analysis, the data recorded as a function of time must be converted to a function of the engine operating mode. To avoid “unnecessary” data in the mode field - formally, by mode parameters related to this mode, but by other parameters falling out of it and blurring the result, you need to use the filtering mechanism. To solve the problem of sorting large (several hours) time fragments of the engine operation in real operation conditions, as well as filtering them, the DataConvert program was written. This program allows you to assign any two of the registered or calculated on their basis parameters, as determining the mode, and the remaining parameters are considered in their function. The program also has several filters to exclude certain engine operating modes from consideration. A screen copy of this program is shown in Fig. 5. With this method of processing the obtained data, it becomes possible to compare the parameters of operation and control of the engine, obtained in different periods of time, as well as the engines of different cars of the same type.
Figure 5. DataConvert program at the stage of setting the filter of the internal combustion engine operating modes.

Data from the ECM is an alternative to recording oscillograms of signals from sensors and actuators for an in-depth study of the operation of the internal combustion engine - direct or indirect indication.

6. Indirect indication technique based on crankshaft position signal processing and direct indication data.

When processing the signal from the crankshaft position sensor, you can get the angular velocity and its change - acceleration - of the crankshaft. But on the crankshaft, in addition to torques from external forces - gas forces, payload and resistance forces - internal - inertial ones act. They do not change the total kinetic energy of the moving parts of the engine, but change the angular velocity of the crankshaft. To exclude their influence from consideration, it is necessary to analyze not the angular velocity of the shaft, but the total kinetic energy of the moving parts of the internal combustion engine. When developing a method for indirect indication, it was decided to use two forms of connection between torque and shaft rotation - differential and integral. The differential form connects the instantaneous acceleration of the crankshaft and the total torque acting on it; integral - the change in the kinetic energy of the moving parts of the engine for a certain angular interval with the work of external forces at the same interval.

According to Newton's second law, the angular acceleration of the crankshaft must obey the relationship:

$$\epsilon = \sum \frac{M}{J_k}$$  \hspace{1cm} (1)

where:
- \(M\) - total torque acting on the crankshaft;
- \(J_k\) - moment of inertia of rotating engine parts.

Let's list the components of the total torque:
\[ \sum M = M_g + M_i + M_f + M_l, \]  

(2)

where:

- \( M_g \) - torque from gas forces, when indicated, it can be calculated with acceptable accuracy;
- \( M_i \) is the moment of inertial forces from parts performing reciprocating and plane-parallel motion. With known geometric dimensions, the mass of the piston set and the connecting rod, this component of the total torque can also be calculated with sufficient accuracy;
- \( M_f \) - the moment of internal losses;
- \( M_l \) - the moment of the payload - in this work, the operation of the engine without external load is considered, therefore it is equal to zero.

Integral relationship between torque and crankshaft rotation:

\[ A_e = \int_{\varphi_s}^{\varphi_e} \sum M_{out}, \]  

(3)

where:

- \( M_{out} \) - torque from external forces,

\[ \sum M_{out} = M_g + M_i + M_f, \]  

(4)

then:

\[ \Delta E_{kin} = A_e, \]  

(5)

where:

\[ \Delta E_{kin} = \frac{1}{2} k(\omega^2(\varphi_e) - \omega^2(\varphi_s)) + \frac{m_p(v_p^2(\varphi_e) - v_p^2(\varphi_s))}{2}, \]  

(6)

where:

- \( \omega \) is the angular speed of the crankshaft;
- \( \omega(\varphi_s) \) - angular velocity at the beginning of the considered section;
- \( \omega(\varphi_e) \) - angular velocity at the end of the considered section;
- \( m_p \) is the mass of parts that reciprocate;
- \( v_p \) - the speed of the parts making a reciprocating motion;
- \( v_p(\varphi_s) \) - speed at the beginning of the considered section;
- \( v_p(\varphi_e) \) - speed at the end of the considered section.

To calculate the kinetic energy of the moving parts of the internal combustion engine, it is required to know the kinematics of the crank gear the moment of inertia of the rotating parts, the mass of the piston, the mass of the connecting rod and its moment of inertia. Of all these parameters, the most difficult is the determination of the moment of inertia of rotating parts. This task - the experimental determination of the moment of inertia of rotating parts of an internal combustion engine based on the action of inertial forces from pistons and connecting rods - was solved in the process of working on a master's thesis. After determining all these parameters, the kinetic energy of the moving parts of the internal combustion engine is calculated as a function of the rotational speed and angular position of the crankshaft.

The next step in the developed indirect indexing technique is to determine the moment of drag forces in the internal combustion engine as a function of the speed, load, and angular position of the crankshaft.

Further, assuming that the moment of the payload in the angle of rotation changes insignificantly, it is necessary to obtain a relationship between the torque determined on the basis of direct indication
and the change in the kinetic energy of the moving parts of the internal combustion engine determined based on the signal of the crankshaft position sensor. If, according to the results of the indication in road conditions, it is proved that the torque calculated on the basis of the signal from the crankshaft position sensor corresponds with the specified accuracy to the torque obtained during the indication, then the problem of indirect indication can be considered solved.

7. **Prospects for creating a complex that allows you to receive feedback from the car during its operation.**

The complex, which allows realizing "feedback" with the car during its operation, should combine simplicity, reliability, small dimensions and high information content. This can be obtained by combining data acquisition from the ECM and recording oscillograms of standard and additional sensors. A significant part of the engine operating parameters, and in a normalized form, can be obtained avoiding the laborious connection to data lines, directly from the ECM, to carry out their primary processing and remotely send them to the monitoring center, where they must form a database. The technical solution - an adapter installed in the diagnostic socket of a car, working wirelessly with a mobile device - has existed for a long time.

To fundamentally expand the capabilities of the complex, in addition to the digital communication line with the ECM, it requires several ADC channels to connect the signal from the crankshaft position sensor and additional external sensors - cylinder pressure, accelerometers. This is demonstrated in Figure 6.

![Figure 6. Diagram of a promising complex for obtaining feedback from a car.](image)

Engine-specific calibrations are determined from a test drive with cylinder pressure sensors. Later, already without pressure sensors, using the method of indirect indication, it becomes possible to determine the instantaneous torque generated by the engine, that is, it becomes possible to monitor the progress of the working process in the engine cylinders.

At the moment, there is no such complex, but we are already working on its prototype.

The increasing complexity of engine management systems creates a demand for feedback mechanisms with it under operating conditions. The main task along this path is to create an optimal algorithm for collecting, processing and cataloging the data obtained.
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