A method and instruments to identify the torque, the power and the efficiency of an internal combustion engine of a wheeled vehicle

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Abstract. In this paper, we propose a new method and instruments to identify the torque, the power, and the efficiency of internal combustion engines in transient conditions. This method, in contrast to the commonly used non-demounting methods based on inertia and strain gauge dynamometers, allows controlling the main performance parameters of internal combustion engines in transient conditions without inaccuracy connected with the torque loss due to its transfer to the driving wheels, on which the torque is measured with existing methods. In addition, the proposed method is easy to create, and it does not use strain measurement instruments, the application of which does not allow identifying the variable values of the measured parameters with high measurement rate; and therefore the use of them leads to the impossibility of taking into account the actual parameters when engineering the wheeled vehicles. Thus the use of this method can greatly improve the measurement accuracy and reduce costs and laboriousness during testing of internal combustion engines. The results of experiments showed the applicability of the proposed method for identification of the internal combustion engines performance parameters. In this paper, it was determined the most preferred transmission ratio when using the proposed method.

1. Introduction
Identification of the main performance parameters of an internal combustion engine (IC engine), among which are the power, the torque, and the efficiency, is an important task in the way of improving the IC engine characteristics. Moreover, since the actual operating conditions of the IC engine are rapidly varying, i.e. preferably transients take place; therefore it is preferred to identify the above mentioned parameters in these conditions. All this allows us to state the importance and topicality of the research to develop the method to identify the performance parameters of IC engines of wheeled vehicles in transient conditions.

Currently, it is preferably to use non-demounting methods to control the performance parameters, which are less labor and energy intensive. Unfortunately at the moment there is a small amount of works dedicated to the development of new non-demounting methods and instruments to identify the IC engine performance parameters, which are measured nowadays with roller dynamometers [1, 2]. In this case the measurements are carried out on the driving wheels of the vehicle, and this leads to...
inaccuracy connected with the fact that the obtained values of output parameters differ from the actual values of an internal combustion engine parameters due to the losses in transmission and friction units. To determine the actual values of the unknown parameters, it is necessary to dismantle the engine from the vehicle [1–5].

The purpose of this paper is to develop the method to identify the performance parameters of an internal combustion engine in transient conditions without its demounting from a vehicle and without the torque loss due to transfer of the power to the driving wheels, on which the torque is measured with the existing methods. The developed method is supposed to be implemented without the use of expensive equipment and strain measurement instruments.

2. Materials and Methods

2.1. Method to Identify the Performance Parameters of an IC Engine of a Wheeled Vehicle

Prerequisites for the implementation of the method: a vehicle, located on the solid asphalt road surface; an internal combustion engine, which is equipped with a sensor of the crankshaft position and with a sensor of the fuel consumption; a hardware-software complex for measuring the angular acceleration of an engine crankshaft (based on the products of the company National Instruments, analog-to-digital converter (ADC) of the type USB-6009, software environment LabView Signal Express 2.5). Acceleration of the vehicle should exclude slippage of drive wheels.

Let us consider the kinematic scheme of the 4-wheeled rear-steer vehicle (see Figure 1).

![Figure 1. Kinematic scheme of the 4-wheeled rear-steer vehicle: 1 is an IC engine; 2 is a clutch; 3 is a gearbox; 4 is a main gear; 5 is a final drive.](image)

The determination of the moment of inertia normalized with respect to the crankshaft rotation axis is made on the assumption that the IC engine should transfer the mechanical energy, which is necessary to drive the wheels, through a kinematic transmission. Each of the wheels has the weight and the radius taking into account the deformation of a tire, rt. At a first approximation each wheel sustains a quarter of the whole weight both of the vehicle with a driver, mv, and of the weight of a reference body (a passenger), mref.

According to [6] the equivalent moment of inertia of the rotating masses is the moment of inertia of a system consisting of elements, which have kinetic energy equal to the amount of the kinetic energy of the whole system.

It follows from the condition of conservation of the kinetic energy that for a system consisting of four wheels interconnected through gears and rotating at the angular velocity, \(\omega_w\), which have the total moment of inertia, \(J\Sigma_w\), taking into account the vehicle linear speed, and neglecting the effect of air resistance, we get the next Equation:
\[ J_{\text{equiv}}(\omega) \frac{\omega_e^2}{2} = J_e k_{e,\text{loss}}(\omega) \frac{\omega_e^2}{2} + J_{tr} k_{tr,\text{loss}}(\omega) \frac{\omega_e^2}{2} + 
\] 
\[ + J_{\Sigma w} k_{w,\text{loss}}(\omega) \frac{\omega_w^2}{2} + (m_v + m_{\text{ref}}) \frac{V_v^2}{2} \] 

where, \( \omega_e \) is the angular velocity of the IC engine, rad/s; \( m_v \) is the weight of the vehicle, kg; \( m_{\text{ref}} \) is the weight of the reference body (a passenger), kg; \( J_e \) is the IC engine rotating parts moment of inertia normalized with respect to the crankshaft rotation axis, kg\cdot m^2; \( k_{e,\text{loss}} \) is the coefficient characterizing the losses in the IC engine \((k_{e,\text{loss}} > 1)\); \( J_{tr} \) is the equivalent moment of inertia of the transmission units, kg\cdot m^2; \( k_{tr,\text{loss}} \) is the coefficient characterizing the losses in the transmission units \((k_{tr,\text{loss}} > 1)\); \( k_{w,\text{loss}} \) is the coefficient characterizing the losses in the wheels \((k_{w,\text{loss}} > 1)\).

From Equation 1 we can determine the equivalent moment of inertia of the whole system:

\[ J_{\text{equiv}}(\omega) = J_e k_{e,\text{loss}}(\omega) + J_{tr} k_{tr,\text{loss}}(\omega) + 
\] 
\[ + J_{\Sigma w} k_{w,\text{loss}}(\omega) \frac{\omega_w^2}{\omega_e^2} + \frac{(m_v + m_{\text{ref}}) V_v^2}{\omega_e^2} \] 

(2)

The transmission ratio between the engine and the drive wheel is equal to the product of the transmission ratio of the gearbox \((k_{gb})\), the transmission ratio of the main gear \((k_{mg})\), and the transmission ratio of the final drive \((k_f)\).

Hence, the Equation 2 can be written as:

\[ J_{\text{equiv}}(\omega) = J_e k_{e,\text{loss}}(\omega) + J_{tr} k_{tr,\text{loss}}(\omega) + 
\] 
\[ + J_{\Sigma w} k_{w,\text{loss}}(\omega) \left( \frac{1}{k_{gb} k_{mg} k_f} \right)^2 + 
\] 
\[ + \frac{(m_v + m_{\text{ref}}) V_v^2}{\omega_e^2} = J_e k_{e,\text{loss}}(\omega) + J_{tr} k_{tr,\text{loss}}(\omega) + 
\] 
\[ + \left( J_{\Sigma w} k_{w,\text{loss}}(\omega) + (m_v + m_{\text{ref}}) \cdot r_t^2 \right) \left( \frac{1}{k_{gb} k_{mg} k_f} \right)^2 \] 

(3)

The engine torque at the angular velocity of the crankshaft, \( \omega_e \), can be determined as:

\[ M(\omega) = J_{\text{equiv}}(\omega) \cdot \varepsilon(\omega) = \left[ J_e k_{e,\text{loss}}(\omega) + J_{tr} k_{tr,\text{loss}}(\omega) + 
\right. 
\] 
\[ \left. + J_{\Sigma w} k_{w,\text{loss}}(\omega) + (m_v + m_{\text{ref}}) r_t^2 \right] \left( \frac{1}{k_{gb} k_{mg} k_f} \right)^2 \varepsilon(\omega). \] 

(4)

The torque during acceleration of the vehicle with the driver (when the accelerator is all the way down) can be defined as:
\[
M(\omega) = \left[ J e k_{e,\text{loss}}(\omega) + J r k_{r,\text{loss}}(\omega) + \frac{J_{\Sigma e} k_{w,\text{loss}}(\omega) + m_r r_i^2}{k_{gb} k_{mg} k_{fd}} \right] \cdot \varepsilon_1(\omega),
\]

where, \( \varepsilon_1(\omega) \) is the angular acceleration of the IC engine during speeding up of the vehicle with a driver, rad/s\(^2\).

Estimated Equation of the torque when accelerating the vehicle with a driver and the reference body (a passenger) (when the accelerator is all the way down) can be defined as:

\[
M(\omega) = \left[ J e k_{e,\text{loss}}(\omega) + J r k_{r,\text{loss}}(\omega) + \frac{J_{\Sigma e} k_{w,\text{loss}}(\omega) + (m_r + m_{\text{ref}}) r_i^2}{k_{gb} k_{mg} k_{fd}} \right] \cdot \varepsilon_2(\omega),
\]

where, \( \varepsilon_2(\omega) \) is the angular acceleration of the IC engine during speeding up of the vehicle with a driver and the reference body (a passenger), which has a weight of \( m_{\text{ref}} \) rad/s\(^2\).

Equating Equation 5 with Equation 6, one can determine the sum:

\[
J e k_{e,\text{loss}}(\omega) + J r k_{r,\text{loss}}(\omega) = m_{\text{ref}} r_i^2 \cdot \varepsilon_1(\omega) - \varepsilon_2(\omega) \cdot \frac{J_{\Sigma e} k_{w,\text{loss}}(\omega) + m_r r_i^2}{k_{gb} k_{mg} k_{fd}}.
\]

Substituting Equation 7 into Equation 5, one can determine the value of the torque developed by the engine itself as:

\[
M(\omega) = \frac{m_{\text{ref}} r_i^2}{k_{gb} k_{mg} k_{fd}} \cdot \varepsilon_2(\omega) \cdot \left( \frac{\varepsilon_2(\omega)}{\varepsilon_1(\omega) - \varepsilon_2(\omega)} + 1 \right).
\]

The power developed by the engine one can determine as:

\[
N(\omega) = M(\omega) \cdot \omega = \frac{m_{\text{ref}} r_i^2}{k_{gb} k_{mg} k_{fd}} \cdot \frac{\varepsilon_1(\omega) \varepsilon_2(\omega)}{\varepsilon_1(\omega) - \varepsilon_2(\omega)} \omega.
\]

After measuring the mass, the fuel consumption, \( Q(\omega) \), at the angular accelerations \( \varepsilon_1 \) and \( \varepsilon_2 \) (ideally, values of the fuel consumptions must be equal) with the known fuel calorific value, \( q_{fc} \), the effective coefficient of efficiency of the wheeled vehicle is determined as:

\[
\eta(\omega) = \frac{N(\omega)}{Q(\omega) \cdot q_{fc}}.
\]

2.2. The Instruments to Identify the Mechanical Parameters of an IC Engine.

For identification of the performance parameters of an internal combustion engine of wheeled vehicles during the full life cycle, it is proposed a hardware-software complex (Figure 2).
Figure 2. Hardware-software complex for identification of the performance parameters of IC engines of wheeled vehicles: 1 – laptop; 2 – high-speed data acquisition and data processing system; 3 – modified crankshaft position sensor; 4 – high-precision digital fuel flow meter.

The configuration of the hardware-software complex: digital information module (USB-6009) manufactured by National Instruments; laptop Acer Extensa 5210; licensed development environment for virtual instrumentation LabView 7.2 with integrated module Signal Express 2.5; high-precision digital fuel flow meter (11,500 pulses per liter) manufactured by Biotech GmBH; modified crankshaft position sensor. Modifying of the crankshaft position sensor lay in the fact that the two main output leads were connected to the two conductors which were, in turn, connected to the digital information module.

3. Results and Discussion
Figures 3–5 show the results of measurement of the efficiency of the experimental vehicle VAZ-2112 (the engine capacity is 1,500 cm³, the rated power is 71 HP at 5,600 rev/min, the torque is 104 N×m at 3,400 rev/min, the transmission ratio of the main gear is 3.7, the distance from the axis of rotation of the drive wheel to the center point of the contact is 0.275 m) of the total weight of 1,030 kg. As a reference body was a passenger, the weight of whom together with the clothes was 71 kg. The weight of a car driver together with the clothes was 95 kg. Figures 3–5 show two curves defined by the Equation 11 when the effective values of the torque were determined by the Equation 8 or Equation 9. The dependencies were obtained with a help of the specialized hardware-software complex, as discussed above.
Figure 3. The efficiency of the engine of the wheeled vehicle VAZ-2112 when speeding up in the second gear (transmission ratio is 1.95).

Figure 4. The efficiency of the engine of the wheeled vehicle VAZ-2112 when speeding up in the third gear (transmission ratio is 1.357).

Figure 5. The efficiency of the engine of the wheeled vehicle VAZ-2112 when speeding up in the fourth gear (transmission ratio is 0.941).
In Figures 3–5 we can see that the values of the efficiency at the different angular velocities of the IC engine are very similar when measured in the second gear that is when the total transmission ratio is 1.95x3.7 = 7.215. With a lower transmission ratio, there are significant differences, so we recommend using the developed method by the speeding up of the vehicle in the second gear.

Figure 6 and Figure 7 show the speed-torque and the speed-power curves of the IC engine of the wheeled vehicle VAZ-2112 when speeding up in the second gear.

The speed-torque and the speed-power curves are calculated based on the approximate values of $\varepsilon_1$ and $\varepsilon_2$.

The experiments showed the level of reliability of the results obtained by the proposed method by comparing them with the certificate data of the test IC engine. It should be borne in mind that the torque value specified in the certificate was obtained with the strain gauges by measuring the required value directly on the engine dismounted from the vehicle. According to the certificate of the VAZ-2112 engine with the capacity of 1,499 cm$^3$, it develops the torque of 104 N×m at the engine speed of 3,400 rev/min (the power is 37.0 kW) using the regular software. According to the experimental data
the value of the torque at 3,400 rev/min is about 105 N ∙ m. The discrepancy between the experimentally obtained value and the certificate value is approximately 1%.

These results support the idea that the external characteristic of an IC engine remains practically unchanged while increasing its inertial mass (additional body with the reference moment of inertia). Thus it is confirmed the validity of the Equation 9 and Equation 10.

The experiments have shown the adequacy and the effectiveness of the developed method and have provided new data on the performance parameters of the internal combustion engine of the wheeled vehicle VAZ-2112. The experimental results made it possible to determine the most preferred transmission ratio of the wheeled vehicle VAZ-2112 (the second gear) when speeding up for performance parameters identification with a help of the developed method.

The proposed method solves from our point of view the most important problem of accurate identifying the performance parameters of an IC engine itself without its demounting from a vehicle. In modern mechanical engineering there are two methods to measure the power and the torque of the IC engine: with and without demounting the engine [1, 2, 4, 7]. The first method allows measuring the torque directly on the crankshaft, which gives a more accurate picture of the engine external mechanical characteristics as compared with the second one. If measurements are carried out without demounting the engine, it is currently used roller dynamometers (see Figure 8). Thus the mechanical power delivered to the drive wheels of the vehicle is determined.

![Figure 8. Roller dynamometer.](image)

Roller dynamometers in turn are divided into two much used types: with inertia dynamometers (inertial method) and with strain gauge dynamometers (brake method).

When measured with strain gauge dynamometers [2, 3, 8] for building external mechanical characteristics, it is used the force sensors that should be previously calibrated precisely, in order to determine the torque at each point at a particular rpm value. Application of DC dynamometers on each drum and electrically controlled clutch allows configuring the treadmill depending on the required measurement. Using the integrated inertial mass, one can perform both steady state and dynamic tests [8]. However, the torque control is carried out with relatively large discrecity, which is due to the time needed to restore strained state of the piezoresistor. Besides this method requires expensive cooling systems, brake equipment and force sensors. Also, there are such drawbacks as the considerable period of full load, low accuracy as compared with the inertial method; temperature errors and limited brake control leads to deterioration in the accuracy of measurement under load. Much of the work devoted to the study of the performance parameters of IC engines are made on the basis of the strain measuring instruments.
The principle of the inertial method is to determine the mechanical characteristics of the engine when accelerating the whole system of rotating masses with additional inertial mass (flywheel), the moment of inertia of which is known [5]. The drive wheel power is defined as the ability to perform a certain work at a time unit. That is, the work is calculated as the energy transferred from the drive wheel to the flywheel at a time unit:

\[ W = \Delta E_c = E_{c2} - E_{c1} = \frac{1}{2} J \omega_2^2 - \frac{1}{2} J \omega_1^2 \]  

(11)

\[ P = \frac{W}{\Delta t}, \]  

(12)

where, \( \omega_2 \) is the angular velocity of the flywheel at the moment of time \( t_1 \), rad/s; \( \omega_2 \) is the angular velocity of the flywheel at the moment of time \( t_2 \), rad/s; \( J \) is the moment of inertia of the flywheel, kg·m²; \( P \) is the power of the drive wheel, W.

The inertial method in comparison with the brake one has a number of advantages associated with the simplicity of the method that is easy to reproduce, and with the applicability to internal combustion engines of any power. Also it does not have other drawbacks, which are inherent in the brake method (does not require expensive cooling systems, the measuring time is minimal, etc.).

However, when using both inertial and brake methods without demounting of an IC engine to identify its performance parameters, a problem to determine the power developed by the IC engine itself remains unsolved.

In contrast to the described existing methods the proposed in this paper new method to control the performance parameters of internal combustion engines solves the problem of identifying the required parameters without loss in transmissions and friction units of a vehicle through the use of a body (a passenger) with the reference weight and the assumption that when the moment of inertia of rotating masses (an internal combustion engine, transmission units and drive wheels) is changed, external characteristic (the speed-torque curve) of an internal combustion engine remains unchanged. In addition there is no need for the use of a strain gauge and other expensive equipment that provides an additional advantage of the developed method. Thus the use of this method can greatly improve the measurement accuracy and reduce costs and laboriousness during testing of internal combustion engines.

4. Conclusion

Based on the results obtained we can conclude that the developed method to identify the performance parameters of internal combustion engines allows controlling their performance parameters by measuring the angular acceleration of the rotating masses with a reference body (a passenger) and without it. This method greatly increases the accuracy of the control compared with other existing non-demounting-engine methods due to the lack of the need for strain gauge elements and to the possibility to identify the performance parameters of internal combustion engines without the torque loss in transmission and friction units.

For the first time designed hardware-software complex allows controlling the efficiency of internal combustion engines and identifying the studied dependences in a wide speed range with a high frequency rate.

The results of conducted experiments showed the most preferred transmission ratio of the wheeled vehicle VAZ-2112 (the second gear) to identify the performance parameters with a help of the developed method.

The developed method is easy to create; it differs less labor- and energy-intensity in comparison with existing methods; it does not require a brake tester, and therefore their application significantly reduces material costs for the organization of the test workplace.

The developed method can be used in the companies manufacturing, operating and maintaining wheeled vehicles with IC engines. Defining tolerable levels of the values of the acceleration of rotating masses including internal combustion engines, it is possible to control their power and efficiency.
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