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An electromechanical microprocessor controlled to optimize internal combustion engines

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Abstract. Operating conditions of the special purpose transport systems are usually difficult. Nowadays, there is an extremely important requirement for a reliability and durability the internal combustion engine. These requirements have to be meet through the operation of the engine lubrication system. However, as experience and the results of experimental studies have shown, the classical, mechanical lubrication system is not able to fully meet these requirements. The lubrication system is tasking with partial cooling of working surfaces, removal of spent particles, and most importantly – to reduce the effect of friction in mechanical components. A mechanical lubrication system equipped with a mechanical oil pump cannot fully provide the optimal mode of lubrication of loaded engine components, since the performance of the gear oil pump depends only on the crankshaft speed, while the oil temperature and the load under which the engine is running are not taken into account. So, based on the mathematical model of the optimal lubrication mode, an algorithm and a software for the operation of the electromechanical lubrication system with microprocessor control were created. A parallel operation of the electromechanical lubrication system with a standard mechanical is an adaptive change in engine oil pressure in the main oil line, which corresponds to the dynamics of changes in the external load of the engine. The result of the parallel operation of the electromechanical lubrication system with the standard mechanical is an adaptive change in engine oil pressure in the main oil line, which corresponds to the dynamics of changes in the external load of the engine. So, the optimum mode is provided even at an extreme mode of operation of the engine likely increase its reliability and service life.

Keywords: electromechanical lubrication system, specific load, oil film thickness, optimal oil pressure.

Mikroprocesorsko podprti elektromehanski sistem za optimalno mazanje motorjev z notranjim zgorevanjem

Pogoji delovanja transportnih sistemov za posebne namene so običajno težki. Hkrati obstaja izjemno pomembna zahteva po zanesljivosti in trajnosti delovanja vira moči, za kar skrbi motor z notranjim zgorevanjem. Te zahteve je treba izpolniti s sistemom za mazanje motorja. Iz obstoječih eksperimentalnih študij lahko ugotovimo, da jih klasični mehanski mazalni sistem ne more v celoti izpolniti. Mazalni sistem je zadolžen za delno hlajenje delovnih površin, odstranjevanje izrabljenih delcev in – kar je najpomembneje – zmanjšanje učinka trenja v mehanskih komponentah. Mehanski sistem za mazanje, opremljen z mehansko črpalko za olje, ne more v celoti zagotoviti optimalnega načina mazanja obremenjenih delov motorja, saj je zmogljivost črpalke za olje odvisna samo od števila vrtljajev ročične gredi, ne pa tudi od temperature olja in obremenitve motorja. Na osnovi matematičnega modela optimalnega načina mazanja smo zasnovali algoritem in programsko opremo za delovanje elektromehanskega mazalnega sistema z mikroprocesorskim krmiljenjem. Rezultat vzporednega delovanja elektromehanskega in klasičnega mazalnega sistema je prilagodljiva sprememba tlaka motornega olja, ki ustreza dinamiki sprememb zunanje obremenitve motorja tudi pri največjih obremenitvah. Tako dosežemo optimalno delovanje motorja ter povečamo njegovo zanesljivost in življenjsko dobo.

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1 INTRODUCTION

Internal combustion engines (ICE) of vehicles of any type are periodically subjected to extreme loads, and in special purpose vehicles, the engines run almost constantly in difficult conditions [1]. That is why the ICE reliability and long-term operation is the main factor to ensures aa proper functioning of vehicles.

The ICE is a complex system, its operation depends on many mechanisms that are required to convert thermal energy released due to fuel combustion into a rotational motion of the engine crankshaft [2]. To reduce the friction force and prevent premature wear of parts, all ICEs have a lubrication system [3]. The classic scheme of this system provides for the presence of a gear oil pump with a direct drive from the crankshaft, which through the oil pipelines under pressure supplies engine oil to the most loaded engine parts. This scheme is a simple and reliable solution, however, as its known from the study [4], during engine operation at the start-up and at peak loads, such a lubrication system is not able to fully provide the necessary lubrication mode of the responsible components.

The main ICE components subjected are the bearings of the crank-and-rod mechanism (CRM). They are is under an uneven load, disability the determination of the oil pressure capable of providing the required thickness of the oil film between the working surfaces of the bearings CRM at the current time. Nevertheless, to ensure minimal friction, and therefore high engine efficiency, and minimize wear of working surfaces, and thus ensure its long-term operation, the thickness of the oil film on working surfaces must constantly correspond to the liquid lubrication regime according to the Gersy-Stribeck diagram [5].

The thickness of the oil film (*h)* is an important indicator that affects the value of the coefficient friction (f_{mp}), which is associated with the characteristics of the lubrication mode, the angular velocity of the shaft in the bearing (ω) and the load that causes specific pressure on the bearing surface (p_{sl},) and oil viscosity (μ).

The analytical dependence for the coefficient of friction in the bearings CRM are derived on the basis of known from the source [6] ratios is determined with Eg.1:

$$f_{mp} = \pi \cdot \left(\begin{array}{l} \frac{\mu \cdot \omega}{p_{num} \cdot \psi} \cdot \left(1 - \frac{2 \cdot 10^{-6}}{h_{\min}}\right) + \\ + \sqrt{\frac{\mu \cdot \omega}{p_{num}}} \cdot \left(\frac{2 \cdot 10^{-6}}{h_{\min}}\right) \end{array} \right) \quad (1)$$

where ψ is the relative clearance bearing.

Depending on the engine conditions of loading, starting, operating, and stopping of the engine, the main and connecting rod bearings CRM can be in the following lubrication modes: liquid, hydrodynamic, dry.

According to the known provisions of the modern theory of lubrication [7], the optimal mode is liquid lubrication, because it has no wear and minimal friction. Moreover, as mentioned above, such engine operating conditions as starting, moving the vehicle up or down, due to their imperfection of the classical scheme of the lubrication system lead to the possibility of CRM bearings, both in dry and hydrodynamic lubrication.

Thus, for today it is important to create a ICE system of lubrication the ICE, which would be supply engine oil with the necessary pressure from the bearings CRM to maintain optimal lubrication in all engine conditions. Solving the problem will increase the ICE reliability and efficiency of the ICE and increase its service life.

Studies had shown [8] that this can be achieved through using of an innovative microprocessor electromechanical lubrication system (MELS) of the engine. The proposed MEMSZ includes a microprocessor, an electric oil pump, and sensors for the oil pressure, oil temperature, crankshaft speed (CS), and sensors those determine the external load on the engine.

The usual many modern publications explore the conservation life of the ICE. Thus, in [9], it was proposed to apply the coating of the moving parts of the engine with anti-friction material. This approach is quite effective but at the same time quite costly.

Recently, using special additives to motor oil has become widespread, the mechanism and principle of their action are described in it [10]. However, the using additives for motor oil can adversely affect other parts and processes in the ICE, so manufacturers of automotive equipment are strongly against their use.

An effective approach to solve this problem is the modernization of the lubrication system of the ICE, which is considered in it [11]. The proposed modernization is carried out through the use of a hydraulic accumulator, which leads to a significant complication for the design of lubrication system. Moreover, such modernization reduces the risk of dry friction but does not ensure the stability of maintaining the liquid lubrication regime.

In the previous work of the authors [8], the influence of vehicle traffic conditions on its power plant and was considered. Some studies have been performed in [12, 13], do not take into account the engine load dynamics of during its operation and do not solve the problem of the speed of response of the lubrication system to the change of gaps in CR bearings.

For the synthesis of an electromechanical lubrication system, there is a need to create a mathematical model that adequately describes the lubrication process in CRM bearings. This model should make it possible to determine the conditions of the optimal mode of lubrication of these components, taking into account the action of internal and external factors influencing the ICE. For experimental verification of the effectiveness of the developed models, the practical implementation of an innovative microprocessor electromechanical lubrication system is provided.

2 ANALYSIS IN THE CLASSICAL LUBRICATION SYSTEM AND ITS MODERNIZATION THROUGH BY USING AN ELECTROMECHANICAL DRIVE.

In 2020, the National Academy of Land Forces (Lviv, Ukraine) conducted experimental study to confirm the effectiveness of the microprocessor electromechanical lubrication system. The method of experimental research was performed in next two stages. The first stage consisted the study of mechanical lubrication system and evaluation of its operation during the operation of the engine with a dynamic load. At the second stage, a study was conducted using an electromechanical lubrication system and quality assessment of the ICE units during its operation with extreme external loads.

2.1 Research of the mechanical lubrication system.

To determine the impact on the mechanical lubrication system of the "cold start" of the engine, and its operation under external load, a special research methodology was developed. The object of ~~the~~

experimental research was a four-stroke gasoline engine, which ~~was~~ installed on the welding machine (Figure 1).

To reproduce the dynamic loads of the engine, which ~~occurs~~ during the movement of the vehicle, the engine in the object of study was loaded with a generator of a welding unit, which was connected to a welding station where the metal welding process took place. Electrodes with a diameter of 2 mm to 4 mm were used for welding, which were created by significant change in engine load.

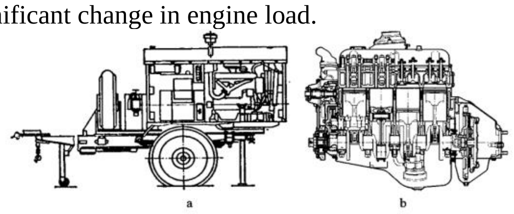


Figure 1. General view of the electric welding unit (a) and its motor (b).

Since the structure of four-cylinder engine is symmetrical and the same processes take place in each cylinder, the simulations and calculations are performed for CMM of a single cylinder.

The measurements and transfer of their results to a computer were carried out using a specially developed microprocessor information-measuring system (MIMS) the generalized structure of which is shown in (Figure 2).

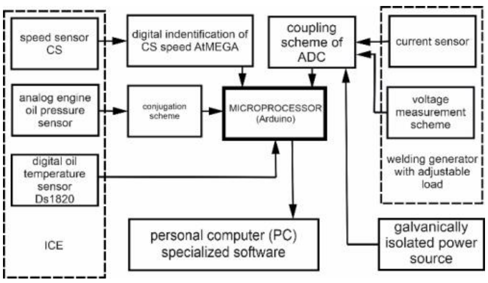


Figure 2. IIS and its generalized block diagram.

The basis of the MIMS is the Arduino-MEGA platform which are connecting sensors of oil pressure, and temperature, crankshaft speed, voltage and current sensors, to measure the voltage and current in the load circuit of the generator. The system allows to carry out automatic measurements in real-time, and to transfer numerical values of measured parameters to the personal computer for their further processing, and visual representation.

In the first part of this experiment, a study of the operation of a mechanical lubrication system under the influence of dynamic load on the engine was carried out, which simulated the conditions of movement of the vehicle. To conduct research, it is necessary to simulate the load on the engine, doing this, we consider the impact of the environment on the movement of the vehicle. As is known [12], the following forces act on the car during movement: P_a - the force of air resistance, P_f - the force of resistance of movement, P_i - the force of resistance of rising, P_J - the force of resistance of dispersal. The sum of these forces causes the occurrence on the engine shaft of the moment of resistance M_r, the value of which can be determined taking into account the above forces, and the design properties of the vehicle transmission by the formula:

$$M_r = \frac{\left(P_a + P_f + P_i + P_j\right) \cdot r_w}{u_{mr} \cdot u_{ge} \cdot u_{ct} \cdot \eta_t \cdot \eta_{te}} \quad (2)$$

where
r_w – is the radius of the wheels;
u_{mr} –is the gear ratio of the matching gearbox;
u_{ge} – is the gear ratio;
u_{ct} – is the gear ratio of the main transmission;
η_t – is the gearbox efficiency;
η_{te} – is the transmission efficiency.

The specified moment of resistance in combination with the force of inertial masses of CRM $F_j = m_{cr} \cdot r_{cs} \cdot \omega^2$ create the load force (F_L) in CRM bearings, which can be calculated with Eg. 3:

$$F_L = \sqrt{\left(\frac{M_r}{r_{cs}} \cdot ctg\left(\alpha + \beta\right) - m_{cr} \cdot r_{cs} \cdot \omega^2\right)^2 + \left(\frac{M_r}{r_{cs}}\right)^2} \quad (3)$$

where: r_{cs} – is the radius of the crankshaft;
α – is the angle of rotation of the crankshaft;
β – is the angle of rotation of the connecting rod;
m_{cr} – is rotating mass of the connecting rod.

In addition to the action of the force caused by an external load on the engine on the bearings, CRM acts by according to the principle of ICE operation. The resultant of these forces (F_Q) is determined by Eg.

$$F_Q = \sqrt{\left(\frac{\left(F_g + F_j\right) \cdot \left(\cos\left(a\right) + \arcsin\left(\lambda \cdot \sin\left(a\right)\right)\right)}{\lambda^2 \cdot \sin\left(a\right)^2 - 1} + m_{cr} \cdot r_{cs} \cdot \omega^2\right)^2 + \left(\frac{\left(F_g + F_j\right) \cdot \left(\cos\left(a\right) + \arcsin\left(\lambda \cdot \sin\left(a\right)\right)\right)}{\lambda^2 \cdot \sin\left(a\right)^2 - 1}\right)^2} \quad (4)$$

where: F_g – is the force of the gas pressure in the combustion chamber;

F_j – is the force of the inertial masses of the piston;

λ – is the ratio of the length of the connecting rod to the radius of the crankshaft.

To study the effect of (F_L) force on the lubrication process, welding electrodes of different diameters are used, which during the welding process, through an electric generator, created a dynamic load on the ICE. With the help of the ICE, the personal computer received information about the engine oil pressure. The load moment M_r that occurred on the motor shaft due to the load from the generator during the welding process is determined by the formula:

$$M_r = 9.55 \cdot \frac{P_w}{n} \qquad (5)$$

where n is the number of revolutions of the engine crankshaft.

The results of this study are shown in Figure 3.

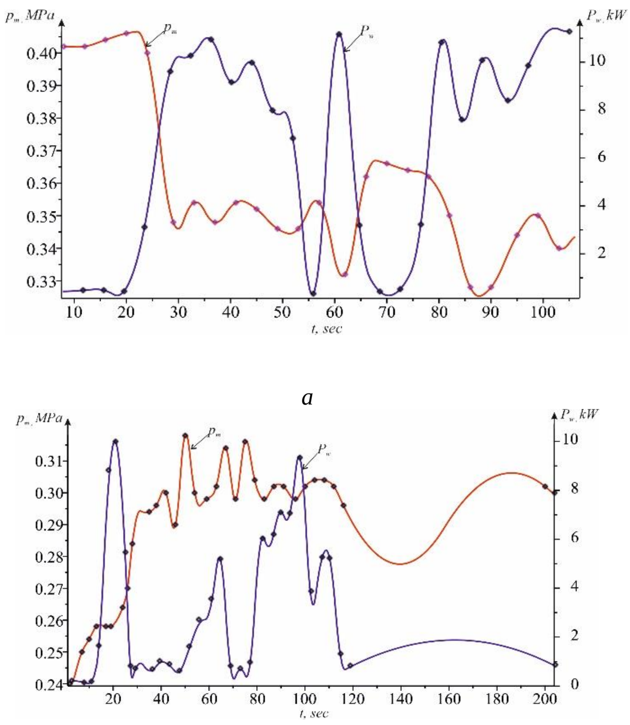


Figure 3. Dynamics of change in power consumption Pw the load circuit of the welding generator for the diameter of the electrodes a) 2 mm, b) 4m, and the corresponding change in oil pressure (p_m) in the ICE lubrication system of the ICE

The analysis of the obtained results confirms–which leads to an increase in the gaps in the unloaded area of the engine crankshaft bearings due to the sum of the force (F_Q) by the piston and the force (F_L) from the external load. As a result, there is a drop of oil pressure caused by the occurrence of eccentricity in the crankshaft bearing, which causes a decrease in the thickness of the oil film [10] in the loaded area. Therefore, there may be the contact of work surfaces without the participation of engine oil, which causes wear of parts and reduces their service life.

Analytically, the process of changing the minimum thickness of the oil film in the loaded area of the bearing pair of the neck-liner pair in the CRM can be described by Eg. 6:

$$h_{\min} = \frac{\mu \cdot n \cdot l \cdot d^3}{18.36 \cdot \delta \cdot c \cdot \left(F_Q + F_L\right)} \qquad (6)$$

where:

d - is the diameter of the connecting rod neck;

l – is the length of the connecting rod neck;

δ – is radial clearance;

$c = 1 + d/l$ – is the bearing shape ratio.

Based on the Eg. 3 (6), computer simulation was carried out on the behavior of the oil film thickness into the loaded area the connecting rod bearing of the engine understudy for one operating cycle, at fixed values of external load. The results of modeling the dependence of ($h_{\min}$) on the angle of rotation of the crankshaft of the engine, (α) are shown in Figure 4.

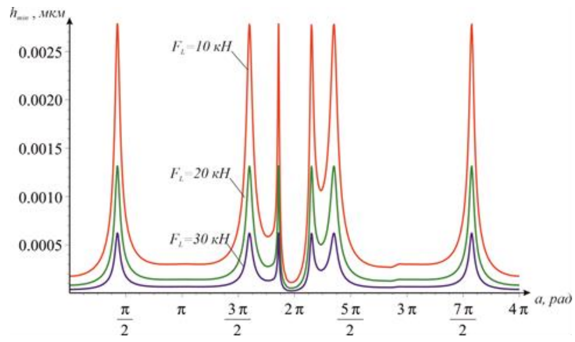
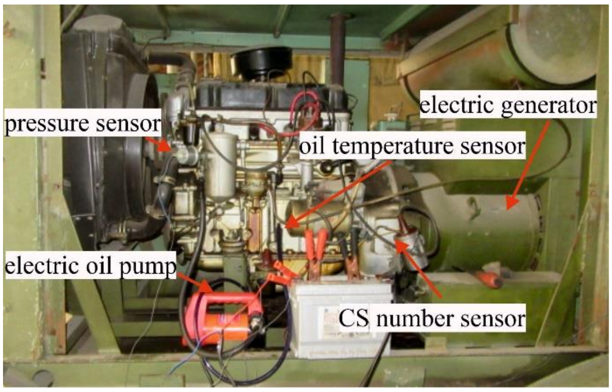


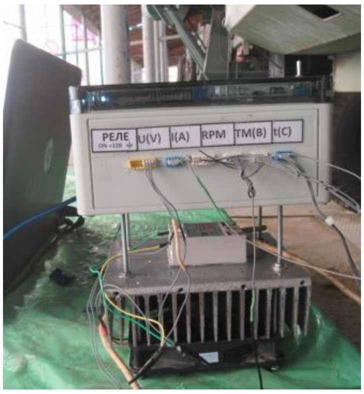
Figure 4. Changing the thickness of the oil film in the loaded area of the bearing for one operating cycle at fixed values of the force (F_L).

The analysis of the obtained results show that by increasing engine load in its main oil line, there is a decrease in oil pressure, which increases the risk of damage to the bearings CRM due to increased likelihood of oil "starvation".

It is obvious that the resulting sum of forces (F_Q + F_L) negatively affects the process of lubrication of the crank bearings due to the fact that the diametric gap (δ) increases significantly, so the volume of engine oil in the loaded area of the bearing decreases rapidly. As a result, the thickness of the oil film becomes smaller ($h_{\min} \leq 2$ μm), which causes the probability of contact of metal surfaces in a pair of connecting rod neck – liner [13].

Thus, the experiments confirmed the obvious shortcomings of the mechanical lubrication system of the ICE.





a *b*

Figure 5: Appearance of the MELS, and its placement on the surface′research project. *a* - placement of the main elements of the system; *b* is the appearance of the EMLS control unit.

2.2 *Evaluation of the efficiency of microprocessor controlled electromechanical lubrication system*

The task of the second stage of the experiment was to solve the problem of ensuring the optimal mode of lubrication of the ICE during its operation with an external load, through the use of an electromechanical lubrication system. For this purpose, an innovative electromechanical lubrication system (EMLS) with microprocessor control was created. Its peculiarity was that in addition to the supplemented software, a power electronics unit was additionally integrated into the previously created MIMS, which allowed to control the DC motor of the oil electric pump by the method of pulse-width modulation.

The EMLS microcontroller is programmed to perform an algorithm for controlling the pump motor, which is based on the use of a mathematical model to create in the oil line of the engine oil pressure required to form the optimal mode of lubrication of the bearing CRM (Eg. 7):

$$p_m(F_Q, F_L, n) = \frac{5.84 \cdot R^2 \cdot \rho \cdot h_{const} \cdot c \cdot \left(F_Q(n) + F_L\right)}{g \cdot q^2 \cdot d^3 \cdot \mu \cdot n} \quad (7)$$

where:

R - is the second oil flow through the bearing CRM;

ρ – is the density of engine oil;

q – is the oil consumption factor through the bearing;

h_{const}= 10 μm;

g – is the free fall acceleration.

To simplify the use of formula (7), the complex analytical dependence (4), which describes the force (F_Q,) was replaced by a third-order interpolation polynomial

$F_Q\ (n) = 38.6 + 4.3 \cdot n + 0.023 \cdot n^2 + 0.53 \cdot 10^{-6} \cdot n^3$, which accurately describes this dependence in a wide range of speeds.

Programmed microcontroller EMLS are provided such a value of oil pressure that allowed to maintain the optimal mode of lubrication of CRM bearings, in which the thickness of the oil layer at any load will not decrease less than (h_{const} = 10 μm) that will provide a liquid mode of lubrication [13]. This considers the change in engine oil temperature and the nonlinearity of the load change on the bearings of the engine crank. The location of the EMLS on the engine of the welding unit and its appearance are shown in Figure 5.

The order of work of EMLS was as follows. Immediately before starting the engine from the sensors of oil temperature, speed, and the oil pressure, the system microprocessor received data on the basis of which the program code was executed according to the programmed algorithm, which are turned on the electric oil pump Thus the problem of the "cold start" of the engine was solved. That is, the start of the ICE was accompanied by a pre-start supply of engine oil, which provided the moving units with the required amount and pressure of engine oil.

After starting the engine, EMLS continued its work, but with the processing of additional information about the influence of external load forces which arose due to the operation of the electric generator during the welding process.

Thus, using of the electromechanical principle of lubrication allowed to provide the loaded components of the ICE with the optimal supply of engine oil, and to take into account all the factors that affect the lubrication process.

3 STUDY OF THE ICE ELECTROMECHANICAL LUBRICATION SYSTEM MICROPROCESSOR-CONTROLLING

The experiment is investigated to the joint operation, a standard mechanical and an innovative microprocessor electromechanical lubrication system. As the results of the experiment showed, it was due to the use of the latter that it was possible to achieve the required change

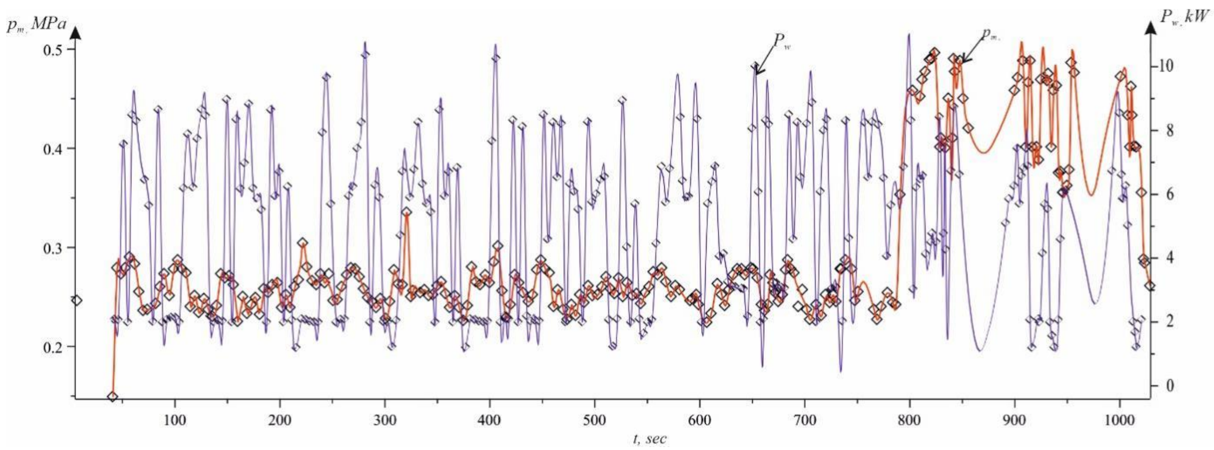


Figure 6: The results of stabilization and load-changing changes in engine oil pressure in the main oil line.

in engine oil pressure in the main oil line so that the bearings of the CRM are constantly in the mode of liquid lubrication. At the same time, a nonlinear change in the viscosity of the engine oil was calculated, associated with changes in temperature and quality characteristics of the oil, as well as the moment of loading, associated with the action of internal factors and the number of revolutions of the CRM, and external load.

Visualization the positive impact of the developed EMC, which reliably demonstrates its performance, the experiment was performed by the EMLS at the 800th second of engine operation. The results of simultaneous measurements of load change and engine oil pressure change are shown in Figure 6.

Analysis of this dependence shows that the proposed EMSS is able to provide such a supply of engine oil, which is necessary for optimal lubrication of the most loaded parts of the engine. Moreover, EMLS is able to ensure a constant stay of the connecting rod bearings CRM in the mode of liquid lubrication, which is stored during engine operation both in normal mode and in extreme loads.

This can be clearly seen from the graph given by the results of the experiment, wherefrom the moment of the 800th second of the experiment the curve of pressure change in the main oil line, thanks to the innovative EMLS began to correspond to the graph of engine power change during the welding process.

4 Conclusion of the results microprocessor electromechanical lubrication system of the internal combustion engine

The main reason for the wear of CRM bearings is the lack of sufficient adaptability of the classical mechanical lubrication system, which is unable to provide optimal lubrication for all modes of engine operation.

Solving the problem of ensuring the optimal mode of lubrication of CRM bearings, taking into account all the factors influencing this process, an innovative microprocessor electromechanical lubrication system was developed.

The influence of external load on the lubrication process of the ICE has been experimentally confirmed. Thanks to a specially developed MIMS during the study of the mechanical lubrication system in real-time information about engine oil temperature, pressure in the main oil line, the number of revolutions of the CS, and the numerical value of the load moment on the engine shaft is processed.

The proposed innovative EMLS was based on the electromechanical principle of operation of the lubrication system.

The create innovative EMLS allowed solving the problem of providing in real time the necessary pressure of engine oil in the main oil line taking into account oil temperature, a wide range of change of the number of turns, and loading of the engine.

Thanks to the use of microcontroller control, the created electromechanical lubrication system is adaptive, suitable for expanding its capabilities and range of tasks.

The main limitations and assumptions that have been accepted in these studies are that the external load on the engine, which in real conditions is caused by the conditions of the transport system, was simulated by a welding electric generator.

Proposed innovative EMLS is universal for all types of four-stroke ICE. After connecting the necessary sensors and entering in the microcontroller data on the parameters of the engine and information about the engine torque, the system can be used without structural changes to the ICE.

In the future, based on the use of a more computationally powerful microprocessor, it is envisaged to create an EMLS with separate oil supply channels at different pressures to different ICE units, which will monitor and maintain the necessary що ???

to create the optimal lubrication mode from the values of all factors influencing the processes of their lubrication.

5 CONCLUSION

1. The work develops a method on the basis of which an experimental study of the mechanical lubrication system of the ICE in the mode of dynamic loads was performed. An electric welding generator was used to simulate loads of the engine of the transport system in extreme traffic conditions. The experiment was performed using a microprocessor information and measurement system. The results of the experimental study correspond to theoretical calculations.
2. According to the results of the experimental study, it is proved that the mechanical lubrication system is unable to supply motor oil to the connecting rod bearings CRM in the required amount. This is due to the fact that the peak values of the external load force create a load moment on the motor shaft, which displaces the crankshaft so that the gap in the pair neck-liner increases. As a result, the engine oil is displaced from the loaded bearing area due to insufficient pressure, which leads to contact of metal surfaces in the bearing, which reduces the service life of the engine.
3. Based on theoretical calculations, a mathematical model is created, which describes the optimal mode of lubrication. This mathematical model takes into account the parameters of engine oil temperature change, the number of CR revolutions, the moment of external load, and internal load. It is shown that this mathematical model takes into account the factors influencing the lubrication process of CRM bearings and allows to calculate the required oil pressure so that during all modes of operation of the ICE these bearings are in liquid lubrication mode.
4. An innovative electromechanical lubrication system of ICE with microcontroller control has been developed and the efficiency of its application has been confirmed by means of a field experiment. This system fully performs the task of providing the most loaded engine parts with the optimal lubrication mode during its operation with extreme external load.

It should be noted that the implementation of the developed EMLS does not require a change in engine design. Because after connecting the electric pump to the oil line, entering the output parameters of a specific type of engine, and installing the necessary sensors, this system can be used in all types of four-stroke ICEs.

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