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ИССЛЕДОВАНИЯ ВЛИЯНИЯ НЕУСТАНОВИВШИХСЯ РЕЖИМОВ РАБОТЫ НА ВЫХОДНЫЕ ПАРАМЕТРЫ ДВИГАТЕЛЯ ЛЕСОТРАНСПОРТНОЙ МАШИНЫ

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Представлены результаты исследовательской работы, цель которой – исследовать влияние неустановившихся нагрузочных режимов на динамические характеристики дизельного автотракторного двигателя лесотранспортной машины. В статье предлагается методика полунатурных испытаний дизельного двигателя и лабораторная экспериментальная установка для исследования влияния неустановившихся режимов работы двигателя на его выходные параметры ($M_e(f)$, $\omega(f)$, $h(f)$, $P_м$, $t_{вг}$); приведены результаты исследования влияния неустановившихся нагрузочных и скоростных режимов работы двигателя на выходные параметры; установлено, что для двигателя ЯМЗ-238НБ существует диапазон частот (f = 0,7…0,9 Гц) изменения момента сопротивления M_c на коленчатом валу, в котором возможно максимальное отклонение основных параметров от средних значений их на сопоставимы установившихся режимах; на основании анализа амплитудно-частотных характеристик колебаний рейки топливного насоса установлено, что в данном диапазоне частот (f = 0,7…0,9 Гц) изменения M_c наблюдается совпадение частот вынужденных колебаний с собственной частотой чувствительного органа регулятора, что приводит систему «двигатель-регулятор» в резонансное состояние.

Ключевые слова: *дизельный автотракторный двигатель, неустановившийся режим работы, выходные параметры двигателя.*

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RESEARCH OF THE INFLUENCE OF UNSTEADY OPERATING MODES ON THE OUTPUT PARAMETERS OF A TIMBER TRANSPORTING MACHINE ENGINE

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The paper presents the results of research aimed at investigating the influence of unsteady load conditions on the dynamic characteristics of a diesel automotive engine of a timber transporting machine. The methodology of semi-full-scale tests of a diesel engine and a laboratory experimental installation for studying the influence of unsteady engine operating modes on its output parameters ($M_e(f)$, $\omega(f)$, $h(f)$, P_o, t_{eg}) is offered. The results of researching the influence of the engine unsteady load and speed modes on the output parameters are presented. It is established that for the YaMZ-238NB engine, there is a frequency range (f = 0.7...0.9 Hz) of changes in the moment of resistance M_r on the crankshaft, in which the maximum deviation of the main parameters from their average values in comparable steady-state modes is possible. On the basis of the analysis of the amplitude-frequency characteristics of the fuel pump rack oscillations, it is found that in this frequency range (f = 0.7...0.9 Hz) of the M_r change the frequencies of forced oscillations coincide with the natural frequency of the governor's sensitive organ, which brings the engine-governor system to a resonant state.

Keywords: *diesel automotive engine, unsteady operating mode, engine output parameters.*

INTRODUCTION

Russia has the world's largest reserves of forest resources (22 % of world reserves). In the composition of Russian forests, coniferous tree species amount to more than 80 % (39 % of larch, 17 % of pine, 11 % of spruce, 6 % of cedar), the main reserves of which are located in the northern and eastern regions of Russia, characterized by severe climatic conditions, complex relief and soil composition. For the industrial use of forest resources, logging equipment is now increasingly being used having powerful general-purpose diesel engines, which were designed without taking into account the peculiarities of operation in the conditions of development of forest resources.

Timber transporting and technological machines operating in the forest industry should be considered as an independent class of machines that have their own specific use and their own operating conditions, determined by terrain, climate, time of year, road or drag condition, soil moisture, machines application technology, etc. [2; 3; 7]. The operation of machines under these conditions is characterized by an increased intensity of changes in speed and load conditions in a wide range of amplitudes and frequencies. The forces of resistance to the movement of a machine along a rack or cutting area, rapidly changing over time, have a significant impact on the operation of the engine, its loading, and cause unsteady operating conditions of the engine, which affects its reliability, efficiency and durability.

The most reliable assessment of the reliability of a diesel engine can be made under real operating conditions. But operational tests require a significant amount of time and money, and the results obtained have a wide scatter, which requires simultaneous conducting of a number of tests. In addition, during operational tests it is difficult, and often impossible, to determine the influence of individual factors on engine wear. Therefore, stand laboratory tests of engines for reliability have become widespread. They can significantly reduce the time and material costs of testing, as well as increase the identity of research results. However, stand tests of engines in accordance with GOST 18509–88 do not provide a number of factors affecting the durability of engines under operating conditions, and in the engine passport, the technical characteristics of the engine do not include its dynamic characteristics, which are important for an engine operating under unsteady conditions.

Particular difficulties arise when studying the influence of unsteady conditions on the wear of main engine parts. This is due to the fact that mass-produced test stands do not allow simulating engine operating modes in laboratory conditions, there are no standard requirements for such testing methods, and there is also no consensus on the concept of the "engine unsteady operating mode". This situation forces researchers to independently develop methods and equipment for testing engines in unsteady operating conditions, and to introduce criteria for unsteady operating conditions. The analysis of the methods and installations used for studying engines in unsteady operating modes showed that for the most part they do not allow simulating a wide range of operating loads.

Thus, the methods and installations developed by Kanarchuk V. E. [5] and Khrushkov P. P. [12] make it possible to study unsteady modes and their effect on the wear resistance of automotive engines. The unsteady mode is considered as a set of transient processes of the speed regime, the duration and sequence of which is determined by the imbalances of the engine torques and the power consumer that arise under operating conditions.

However, in order to determine the influence of individual parameters of unsteady modes on the wear rate of the engine, the sources [5; 12] artificially kept one of them (speed or load) constant, which does not reflect the operating conditions, where the load on the engine and the angular velocity of its shaft simultaneously change.

An original way to eliminate the last drawback inherent in the methods listed above was proposed by V. P. Antipin [1]. A load changing according to a harmonic law in the range (0.01…2.0) Hz was created on the crankshaft of the test engine using an electric braking stand STEU-28-1000, in the stator circuit of which a 3-phase magnetic amplifier controlled by a low-frequency generator of periodic oscillations is connected. The disadvantage of the proposed method of reproducing variable loads on the shaft of the tested engine is that with an increase in the power of the braking device above 100 kW, the installation time constant increases, i.e. the braking device does not allow reproducing loads changing with a frequency of more than 1.5 Hz.

From the analysis of existing methods for studying unsteady operating modes of automotive engines it follows that they do not allow solving the above tasks of studying the characteristics of automotive engines with a power of more than 100 kW. This circumstance required the development of a special installation and methodology for studying the amplitude-phase frequency characteristics of the engine and a methodology for studying the influence of unsteady modes on the wear of a diesel engine with a power of more than 100 kW. The development of the methodology was carried out in accordance with the requirements of GOST 18509–88 based on the analysis of the operating conditions of timber transporting machines.

PURPOSE OF THE RESEARCH

1. Develop a methodology for modeling operational load conditions to study the dynamic characteristics of a diesel engine.

2. Create an experimental laboratory installation to conduct research into the influence of unsteady operating conditions on the output parameters (dynamic characteristics) of a diesel automotive engine and to study the effect of unsteady operating conditions on engine wear.

3. Investigate the influence of the amplitude and frequency of load changes on the dynamic characteristics of the YaMZ 238NB engine.

METHOD AND INSTALLATION TO TEST THE ENGINE

Research of operating modes of skidders [2; 3; 8] showed that at any moment in time the current value of the resistance forces is determined by two components: a constant one equal to (0.75–0.85) Mn, and a variable one equal to 0.15 Mn - the rated torque of the engine.

The frequency spectrum of changes in resistance forces can be divided into two zones [7]: the first zone characterizes the slow process with a period of change (T) of more than 10 seconds ≤ 0.1 Hz. Changing forces in this range is available for regulation by the engine governor and by humans. They are determined by changes in macro conditions and are taken into account by the traction balance equation. Their fairly complete characteristic is the mathematical expectation (μ_x) or the average value and dispersion (D_x), since the engine time constant (T_e) is significantly less than the period of change of these forces and the engine's response to their influence is known in advance.

The second frequency zone characterizes fast processes with a period of less than 10 seconds (0.1 Hz), which can only be controlled by the engine governor. These forces are not taken into account by the traction balance equation and can be characterized by spectral density of a random process, describing the microconditions in which the machine operates.

Due to the lack of a consensus on the physical essence of the unsteady operating mode of the engine, it is advisable to take the process of transition from one speed mode to another [11] under the influence of a change in the moment of resistance M_r as the main element defining this operating mode, since it most fully characterizes the work of an automotive engine in operating conditions.

Under operating conditions of machines during logging, unsteady operating modes of machine engines are random in both frequency and amplitude. It is extremely difficult to reproduce the entire range of loads in full in laboratory conditions, therefore, when developing an installation for studying engine wear, it was proposed to load the engine according to the harmonic law, which says, that according to the first theorem of V. A. Kotelnikov [9], any function (including one describing a random process) with a frequency range from zero to maximum can be spread horizontally in a row, and as the harmonic number increases, its frequency increases and its amplitude decreases, which is observed in nature.

The method of harmonic loading of the engine does not contradict the research of academician V.N. Boltinskii [10], where it is indicated that under operating conditions the moment of resistance on the engine shaft changes according to a quasi-harmonic law.

Based on the above, a methodology [4] for semi-full-scale testing of a diesel engine and a laboratory experimental installation were developed to study the influence of unsteady engine operating conditions on its output parameters. The YaMZ-238NB engine used on tractors K-700, K-703, K-744 and the KrAZ-255L vehicle widely used in the timber industry was chosen as the object of research.

The new engine YaMZ-238NB of serial production was tested. It was run-in on a stand for 60 hours according to the modes recommended by the manufacturer, after which the engine was equipped with additional sensors for monitoring the main parameters of engine operation and all work related to the preparation of the engine for testing was completed. The power limiter was removed and the engine was additionally run for 16 hours in M_e mode = 80 kgm (800 Nm), n = 1500 rpm, N_e = 170 hp. (125 kW), for the purpose of additional running and development of test methods.

According to GOST 18509–88, before starting research on the YaMZ-238NB engine on a brake stand, the nominal and maximum values of effective power and torque, hourly and specific fuel consumption were determined according to the external speed characteristic at crankshaft speeds corresponding to these values. At the same time, measurements were made of: angular velocity of the crankshaft ω, braking torque T_b, effective torque M_e, position of the fuel pump rack h, oil pressure in the lubrication system P_o, exhaust gas temperature t_{eg}, engine indicators P_z. All of the above indicators were recorded on an oscillogram.

Experimental installation for studying unsteady engine YaMZ-238NB operating conditions consists of a load device, a frame for installing the engine under test, a software device, a system of instrumentation and recording equipment (Fig. 1).

A commercially produced test stand KI-598B (asynchronous balancing machine AKB-92-8, power 55 kW) and a load powder brake PT-250 M, power 50 kW are used as a load device. The total braking power of the load device is 160 kW (220 hp).

The engine under test is installed on a frame (front semi-frame of the K-700 tractor) and connected with a load device via a cardan shaft.

The low-frequency generator of periodic oscillations NGPK-3, which sets the law of load changes in the form of a sine wave, triangular, sawtooth or rectangular pulses in the range of 0.06–100 hertz is the software device of the installation. The frequency setting error in the range of 0.1–100 Hz is ± 3 %; amplitude stability – $\pm 0{,}1$ %.

The installation operates as follows (Fig. 2): the low-frequency generator NGPK-3 generates periodic or sinusoidal signals, which are amplified by the amplifier U and supplied to the excitation winding of the powder brake PT, the braking torque of which varies according to the law of the excitation current. Thus, the powder brake reproduces the variable component of the moment of resistance, which is summed with the constant component reproduced by the KI test stand, and arrives at the shaft of the engine under test.

The value of the constant component of the resistance moment is set by the KI brake stand by changing the value of the load resistance R in the rotor circuit of the balancing machine.

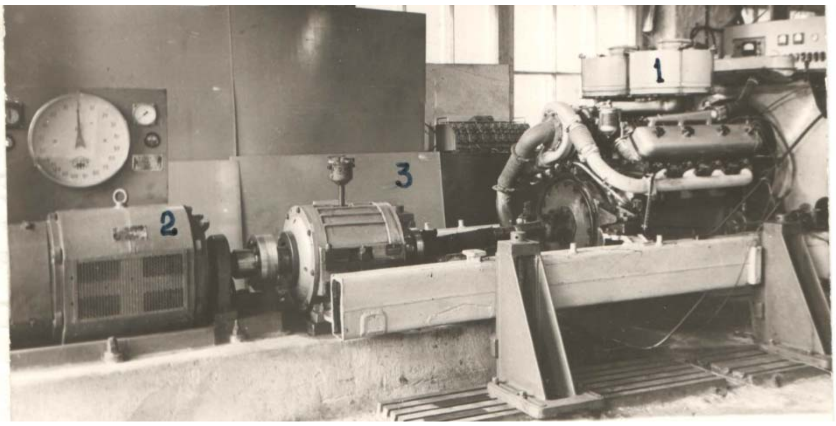

Fig. 1. General view of the experimental installation:
1 – YaMZ-238NB engine; 2 – stand KI-598B; 3 – powder brake PT-250M

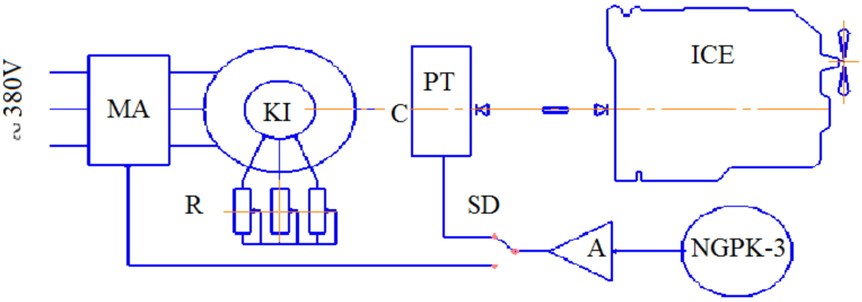

Fig. 2. Installation block diagram:
MA – magnetic amplifier; R – load resistance; KI – test stand KI-598B; PT – powder brake; SD – switching device; A – amplifier; ICE – internal combustion engine; NGPK-3 – low-frequency generator NGPK-3; C – coupling

In this mode, the installation operates at frequencies of change in the resistive torque of more than 1.5 hertz. In the frequency range less than 1.5 Hz, the KI-598B brake stand does not provide a linear dependence of the constant component of the resistance moment; therefore, in the frequency range (0.1–1.5) Hz, the variable component of the resistance moment is modeled by the KI brake, and the constant component - by the powder brake PT. In this case, the software device, using the PC switch, is disconnected from the excitation winding of the powder brake and connected to the control winding of the magnetic amplifier MA in the power supply circuit of the KI brake. The magnetic amplifier ensures a change in the current in the stator circuit of the KI brake, and therefore the braking torque according to the law specified by the software device. The constant component of the moment of resistance in this case is provided by a powder brake PT, the excitation winding of which is connected to a direct current source. Due to the design features and characteristics of the powder brake, the braking torque T_b does not change when the shaft speed fluctuates up to 200 rpm.

Researching the influence of variable loads on engine output parameters

The engine of a timber transporting machine, being an active dynamic object, reacts differently to external influences that vary over a wide range of frequencies and amplitudes. Research into the influence of the dynamic properties of the engine on the technical and economic indicators with a rapidly changing load on the crankshaft comes down to finding, first of all, the dynamic characteristics of the output parameters (angular velocity of the crankshaft ω and torque M_e) as indicators determining its reliability and resource.

From the theory of automatic control [13] it is known that the same dynamic system reacts differently to different input influences. Amplitude-frequency (AFCs) and phase-frequency (PFCs) characteristics were taken as dynamic characteristics of the engine, reflecting the engine's response to external influences. The AFCs of the engine were determined: by the engine torque – as the ratio of the engine torque to the resistance moment $M_e(f)$ / $M_r(f)$; by angular velocity – as the ratio of the angular velocity of the crankshaft to the moment of resistance $\omega(f)$ / $M_r(f)$. Amplitude values of engine torque M_e, angular velocity of the crankshaft ω, as well as the position of the fuel pump rack h, were determined from the oscillogram as their deviations from the average steady-state values.

Phase-frequency characteristics were determined from oscillograms as the phase shift between the input /$M_r(f)$/ and output /$M_e(f)$, $\omega(f)$, $h(f)$/ parameters.

The frequency characteristics of the YaMZ-238NB engine were determined on an experimental installation with a sinusoidal change in the moment of resistance in the frequency range most characteristic for engine operation under operating conditions (f = 0.05–5.0 Hz), in the regulatory region of the speed characteristic. Fig. 3 shows a sample oscillogram of changes in engine output indicators /$M_e(f)$, $\omega(f)$, $h(f)$, P_o, t_{eg}/ at a load M_r = 745 Nm, ω = 136 1/s, δ = 0.20, f = 0.8 Hz. Oscillogram recordings show that the engine output parameters, as well as the resistance torque, are sinusoidal in nature, but with some phase lag.

Graphs of the amplitude-frequency characteristics (fig. 4) were constructed on the basis of the experimental data obtained by decoding the oscillograms.

From the analysis of the AFC and PFC graphs of the angular velocity of the crankshaft, it follows that an increase in the frequency of changes in the input torque from 0.05 to 0.15 Hz is not accompanied by noticeable changes in the deviations of the angular velocity from steady-state oscillations. However, starting from a frequency of 0.2 Hz to 0.8 Hz, the amplitude of deviations in the angular velocity of the crankshaft increases sharply, reaching its maximum at a frequency of 0.8 Hz, which adversely affects the organization of engine operating cycles, causing an increase in dynamic loads on its parts, and therefore contributes to increased wear at these frequencies. A further increase in the frequency of changes in the input torque from 0.8 to 1.25 Hz is accompanied by a damping of the amplitude of angular velocity fluctuations from a maximum value of 11 1/s (at a frequency of 0.8 Hz) to 6.0 1/s (at a frequency of 1.25 Hz). A change in frequency from 1.25 Hz to 3.0 Hz and higher is accompanied by an exponential decay of the angular velocity amplitude to 0.4 1/s, which does not cause noticeable vibrations of the fuel pump rack, and, consequently, disturbances in the organization of the engine operating cycle.

The influence of variable loads on oil pressure in the lubrication system and angular accelerations of the engine crankshaft

The change in the angular accelerations of the crankshaft and pressure in the lubrication system depending on the frequency of changes in the moment of resistance as parameters influencing the wear rate of the main engine parts is of practical interest when the engine operates in unsteady modes in the regulatory region of the speed characteristic.

The angular acceleration of the shaft was calculated using the formula

$$\varepsilon = d\omega \,/\, d\tau \ (1/s^2),$$

where $d\omega$ is the increment in the angular velocity of the crankshaft during the time $d\tau = \Delta\tau$.

At frequencies above 3 Hz, the angular accelerations of the crankshaft do not exceed 0,5 $1/s^2$, i.e., the engine filters these frequencies and its operating mode can be considered steady. Low-frequency components of the amplitude of oil pressure fluctuations in the lubrication system are filtered at frequencies above 2 Hz. The study of oscillogram decoding data is presented in the graph in Fig. 5.

The graph shows that with increasing frequency, changes in the moment of resistance M_r, shaft acceleration ε and the amplitude of pressure fluctuations A_{pf} in the lubrication system increase, reaching their maximum values ($\varepsilon = 54\ 1/s^2$; $A_{pf} = 4 \cdot 10^4\ N/m^2$) at a frequency of 0.8 Hz. Further increase in the frequency of changes in M_r leads to reducing the angular acceleration of the crankshaft and the amplitude of oil pressure fluctuations.

The influence of variable loads on the dynamic performance of the engine operating cycle

It was noted above that during the period of load changes, phase lags in the output parameters of the engine are observed, which have the most unfavorable combinations at a frequency of 0.8 Hz and negatively affect the performance of the operating cycle. Fig. 6 illustrates the nature of changes in the main engine indicators (M_e; ω; ε; h; P_z; $\Delta P/\Delta\varphi$) during the period of change in the moment of resistance at a frequency of 0.8 Hz in the regulatory region of the characteristic at $M_{r.\ av}$ = 745 Nm, ω = 1361 /s, δ_c = 0.20. This mode of engine operation is the most typical for the operating conditions of skidders [2; 3; 7].

From Fig. 6 and 7 it is clear that all output parameters of the engine lag in phase from the moment of resistance M_r: M_e – by 1/4 T, ω – by 1/2 T, h – by 1/8T, P_z – by 3/8T, $(\Delta P/\ \Delta\varphi)_{av}$ – by 3/8T. At this frequency, the amplitude of the engine torque oscillations exceeds the resistance torque by 11 %. The engine torque reaches its maximum when the load is released at a moment of 0.75T, when $M_r = M_{r.\ av}$, which leads to a significant increase in the angular velocity ω and acceleration ε.

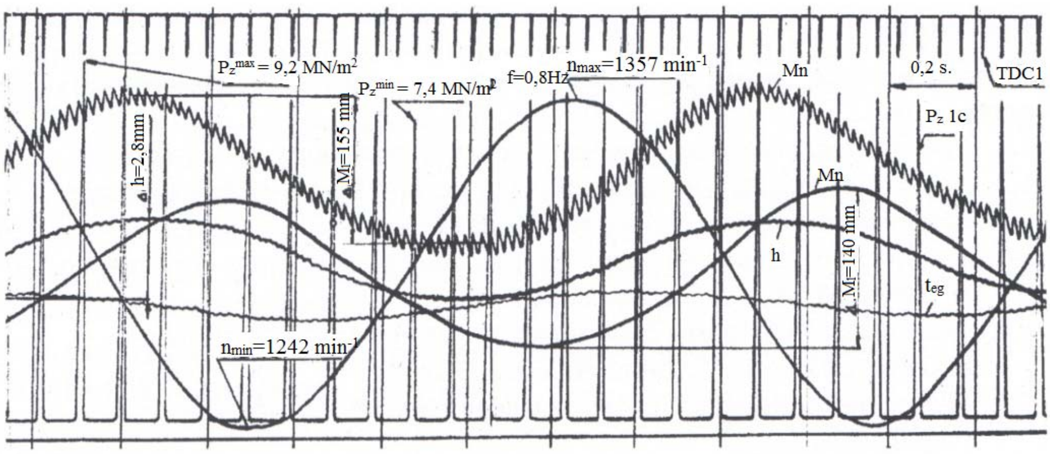

Fig. 3. Oscillogram of engine test at frequency f = 0.8 Hz:
M_r (M_e) – torque; TDC – mark of the top dead center of the piston of the 1-st cylinder; n – crankshaft rotation speed; h – vibrations of the fuel pump rack; t_{eg} – temperature of exhaust gases in the outlet collector; M_l – variable load component; P_z – gas pressure in the combustion chamber of the 1-st cylinder

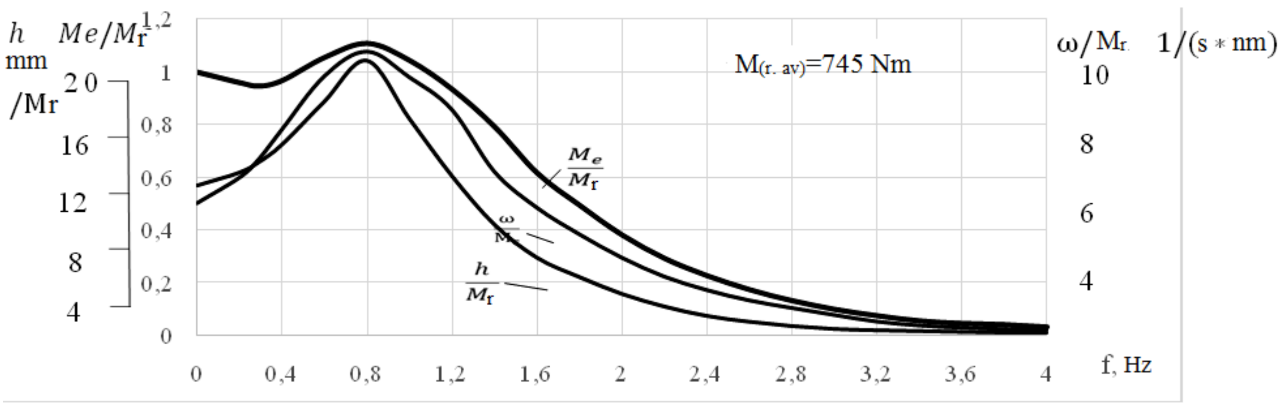

Fig. 4. Amplitude-frequency characteristics of the YaMZ-238NB engine

When the load is released in the first quarter of the period of its change (0...0.25 T), a decrease in the maximum cycle pressure P_z and the average pressure increase $(\Delta P/\Delta\varphi)_{av}$ is observed due to a decrease in engine torque M_e (maximum cyclic fuel supply for the period). In the second quarter of the load change period, the engine torque increases (g_c growth), which leads to an increase in dynamic indicators (P_z, $\Delta P/\Delta\varphi$), which reach their maximum value [P_z = 9.0 mN/m^2 (92 kg/cm^2); $(\Delta P/\Delta\varphi)_{av}$ = 29.6 MN/m^2·rad (5.28 kg/cm^2·deg)] by the middle of the last quarter of the period (0.85 T) of change in the moment of resistance M_r. Minimum values of dynamic cycle indicators [P_z = 7.4 mN/m^2 (75 kg/cm^2); $(\Delta P/\Delta\varphi)_{av}$ = 19.7 MN/m^2·rad (3.52 kg/cm^2·deg)] are reached at (0.25…0.30) T.

It should be noted that, despite the symmetrical nature of the oscillations of the fuel pump rack, its relative position in steady state, the dynamic indicators of the cycle do not maintain such symmetry (Fig. 7). The maximum value of P_z is 12.5 % greater at 0.875T, and the lowest value of P_z is 8 % less than P_z at the corresponding steady state. The average increase in pressure has an even greater deviation from the steady state: $\Delta P/\Delta\varphi)_{av}$ is 32 % more at 0.875T and 10 % less at 0.30T (Fig. 7).

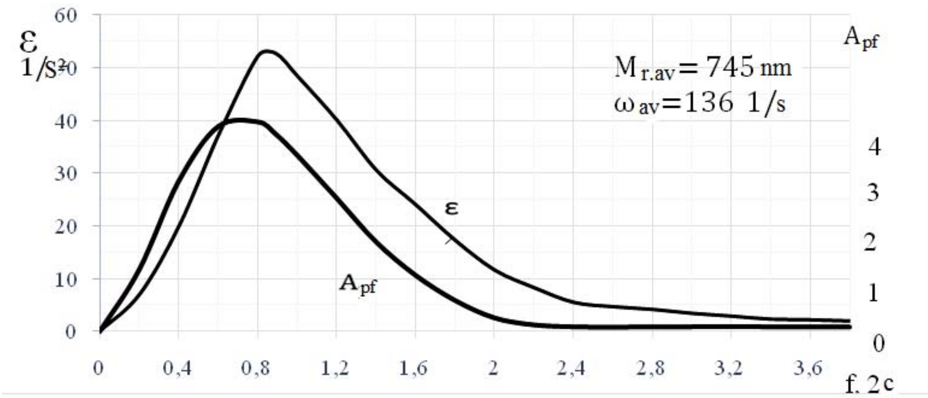

Fig. 5. Dependence of crankshaft acceleration ε and amplitude of oil pressure fluctuations A_{pf} in the lubrication system of the YaMZ-238NB engine on the frequency of change of the moment of resistance M_r

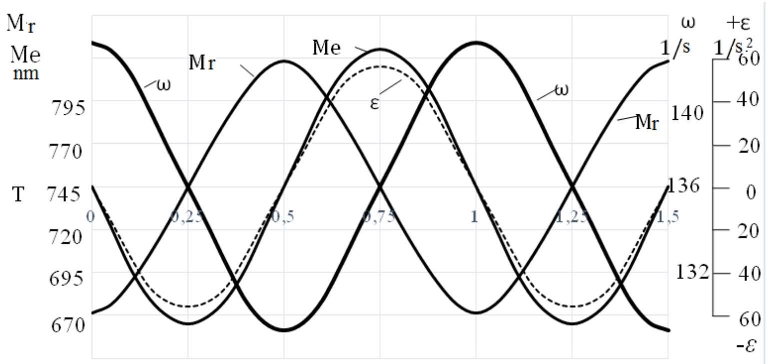

Fig. 6. Change in output indicators M_e, ω, ε of the YaMZ-238NB engine over the period of load changes at a frequency of 0.8 Hz

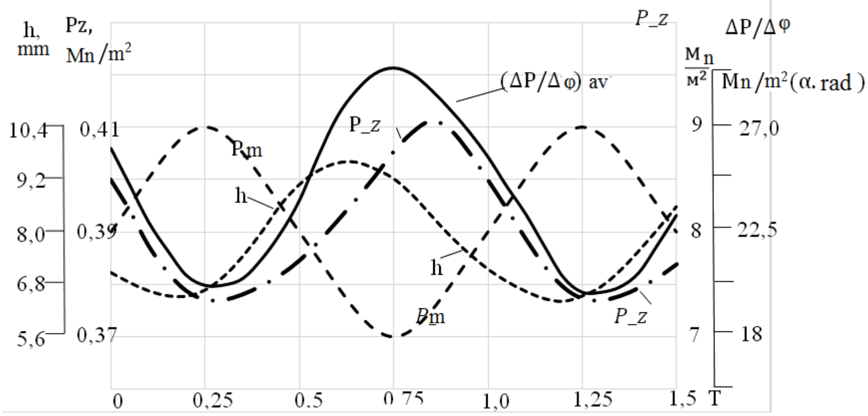

Fig. 7. Change in output and dynamic parameters h, P_z, $\Delta P/\Delta\varphi$, P_m(b) of the YaMZ-238NB engine during the period of load change at a frequency of 0.8 Hz

A significant increase in dynamic performance in the second half-cycle of change in the moment of resistance (load release) is explained by an increase in engine torque and angular acceleration of the crankshaft due to an increase in the cyclic fuel supply (at 0.875T g_c reaches its maximum). The change in engine torque M_e and the angular acceleration of the crankshaft ε are in phase. An increase in acceleration increases the ignition delay period and the duration of the third phase of fuel injection (fuel injection after seating of the injection valve, due to the expansion of the fuel located between the valve and the injector nozzle), which leads to increasing the "rigidity" of the engine operating process.

From the above analysis of the influence of variable loads on engine performance, it follows that in unsteady engine operating modes there is a significant increase in the dynamic performance of the operating cycle (P_z – by 12.5 %; $\Delta P/\Delta\varphi)_{av}$ – by 32 %), compared with comparable steady-state modes. An increase in the dynamic indicators of the cycle ("rigidity" of the working process) leads to an increase in the specific dynamic loads on the interfaces, and, consequently, to an increase in the wear rate of the main engine parts when operating in unsteady conditions.

CONCLUSIONS

1. The proposed methodology for studying automotive engines in unsteady operating modes makes it possible to evaluate their dynamic properties, to study the influence of these modes on the performance of the operating cycle of internal combustion engines, in conditions that are as close as possible to to operational ones.

2. An experimental laboratory installation which makes it possible to create constants with different load levels on the shaft of the tested engine, as well as sinusoidal, pulsed and stochastic variables with a range of 60 dB has been developed and created.

The proposed methodology and the developed installation can be used to carry out accelerated wear tests of automotive engines according to a given program, without resorting to full-scale operational tests.

3. It has been experimentally established that for the YaMZ-238NB engine there is a frequency range of changes in the moment of resistance on the crankshaft (f = 0.7...0.9 Hz), in which the maximum deviation of the main parameters from their average values in comparable steady-state modes is possible.

On the basis of the analysis of the amplitude-frequency characteristics of the fuel pump rack, it was established that in this frequency range (f = 0.7...0.9 Hz) of changes in M_r, there is a coincidence of the frequencies of forced oscillations with the natural frequency of the sensitive organ of the regulator, which drives the "engine–governor" system into a resonant state.

4. Experimental studies have established that the output parameters of the engine, with a sinusoidal change in the moment of resistance in the regulatory region of the characteristics, also change according to the sinusoidal law of the same frequency, but with some phase lag. All parameters reach the maximum deviation in amplitude from the average steady-state values at the frequency of the variable component equal to 0.81 Hz. Under these conditions, there is a phase delay in the angular velocity by 1/2 T, the engine torque by 1/4 T, and the fuel pump rack by 1/8 T.

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