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BUILDING A LOAD CHARACTERISTIC OF THE FUEL INJECTION SYSTEM OF A SHIP'S MEDIUM-SPEED ENGINE DIESEL IN DYNAMIC TESTS CONDITIONS

Об'єктом дослідження в роботі є гідродинамічні процеси в паливній системі високого тиску суднового середньообертового двигуна на змінних режимах. Змінні режими становлять значну частину експлуатаційного часу ряду типів суден (буксири, промислові судна та ін.). А для транспортного флоту вони характерні при маневруванні. В останньому випадку особливе значення має надійність і екологічна безпека для зон санітарного контролю. Дослідження процесів подачі палива на змінних режимах важливі, так як вони в значній мірі визначають всі експлуатаційні характеристики дизеля і недостатньо вивчені.

У роботі представлений експеримент, в якому ставилося завдання отримання навантажувальної характеристики і дослідження перехідних режимів в паливній апаратурі суднового середньообертового дизеля в умовах динамічних випробувань.

В ході дослідження використовувався розроблений апаратно-програмний комплекс, що забезпечує реалізацію плану експерименту, фіксацію, обробку і осциллографування отриманих даних. Розроблено електромеханічну систему переміщенням рейки паливного насоса високого тиску з програмним комп'ютерним управлінням.

Програмою експерименту передбачено зміну положення рейки у всьому діапазоні, що охоплює експлуатаційну навантажувальну характеристику. Дискретне переміщення включало п'ять фіксованих положень рейки зі ступінчастим переходом між ними.

При випробуваннях паливний насос високого тиску зробив 80 циклів впорскування протягом 44 с. Час переходу між окремими фіксованими положеннями рейки становив 0,44 с. Період стабілізації гідродинамічних процесів в системі подачі палива близький до 0,22 с.

У дослідженому діапазоні положень рейки $m_р$=25–5 мм (6 та 59 цикли) основні параметри подачі палива мали такі значення: $p_{ф.к}$=474–232 бар; $p_{ф.вх}$=457–222 бар; $p_н$=445–162 бар.

Проведене дослідження показало можливість отримання навантажувальної характеристики шляхом динамічних випробувань, що істотно скорочує час випробувань і підвищує достовірність даних, виключаючи вплив тимчасового тренда параметрів.

Ключові слова: *середньооборотний дизель, паливна апаратура, апаратно-програмні засоби безмоторних динамічних випробувань, навантажувальна характеристика, змінні режими.*

1. Introduction

Variable modes constitute a significant part of the operational period of transport diesel engines [1]. Because of this, such regimes largely determine all the operational characteristics of such power plants. But also for power plants operating mainly with stable loads, variable modes are of great importance, since their quality characterizes reliability in terms of maneuvering and environmental safety in sanitary control zones.

In these areas, the requirements for the content of the most significant component of harmful substances in the exhaust gases of marine diesel engines – nitrogen oxides – are governed by the norms of the International Maritime Organization (IMO) presented in Fig. 1.

In Ukraine, at present, environmental safety standards for exhaust emissions are regulated by the Euro 5 standard.

To ensure the accepted norms and indicators in the field of diesel construction, research is envisaged in the following main areas [3]:

- improvement of engine design (optimization of the fuel supply process);
- consideration of operational factors (optimization of engine operating conditions);
- use of unconventional fuels.

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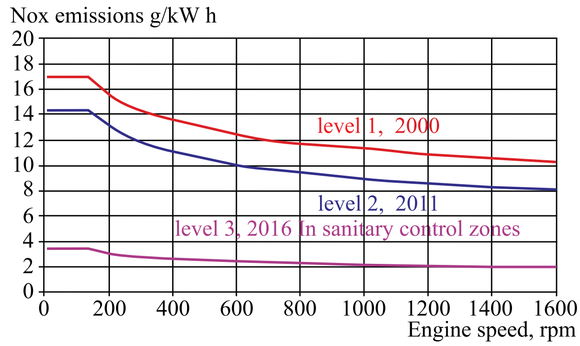

Fig. 1. Requirements of the International Maritime Organization (IMO) to NO_x emissions in waste gases of marine diesel engines (compiled by the author based on data from the source [2])

Research in the field of improving high-pressure fuel systems is aimed at:

– improving the accuracy of dosing cyclic fuel supply;
– optimization of the combustion process in all operating conditions, including during start, idling, acceleration and rundown;
– ensuring optimum efficiency, environmental friendliness and operational reliability.

Since the processes of fuel supply play a decisive role in ensuring all the characteristics of diesel engines, including on variable conditions, research in this area is relevant.

2. The object of research and its technological audit

The *object of research* in this work is hydrodynamic processes in the high-pressure fuel system of a ship's medium-speed engine on variable conditions.

These processes are implemented in the direct feed fuel supply system, which is characteristic of a widespread type of marine engine.

Characteristics of fuel supply largely determine all the operating parameters of diesel engines in all modes, including variables. Simultaneously with the transients, variable loading areas are formed on variable modes.

A joint study of transients and modes of load characteristics has not previously been conducted. The solution of such a problem is of scientific and practical interest and is considered in this work.

3. The aim and objectives of research

The aim of research is obtaining data on changes in the fuel injection parameters of the ship's medium-speed diesel engine with a variable position of the rack of the high-pressure fuel pump under the appropriate modes of load characteristics.

To achieve the aim, the following objectives are set:

1. To determine the dynamic parameters of the transition processes between the modes of load characteristics under dynamic testing conditions.

2. To determine the temporal characteristics of the process-speed of the system transition to a stable mode.

4. Research of existing solutions of the problem

It was previously established [4] that the main factor determining the flow rate characteristic of the fuel injection system is the initial pressure. Tests have shown that under conditions of a non-motorized stand [5] it is possible to build a given characteristic (in this case, speed) within the framework of one experiment. The obtained result serves as the basis for preparing and conducting a similar experiment with the aim of building a load characteristic.

The data established in this way will allow synthesizing the fuel injection process on variable modes corresponding to their actual flow in the engine with simultaneous change in the rotational speed and displacement of the high-pressure pump rack.

When developing diesel fuel injection systems, the requirements of regulatory documents [6] on design solutions and technical and economic indicators are fulfilled. At the same time, research is being conducted aimed at the development of fuel supply facilities and processes. In this case, both steady-state and variable operating conditions are considered.

An integrated approach taking into account economic and environmental indicators is used by the authors of [7] in solving the problem of optimizing fuel equipment.

As a result of the analytical review, the following solutions are proposed:

– optimization of fuel equipment control for each engine mode;
– use of multiphase injection to reduce noise, afterburning of organic components and ensure the operation of the neutralizer;
– flexible control of the injection advance angle depending on the diesel operation mode;
– the maximum possible reduction in the irregularity of the fuel supply in the cylinders;
– self-diagnosis of the fuel system.

In the development of tools to reduce the toxicity of exhaust gases of diesel engines in transient conditions, the main attention is paid to the change of the fuel injection advance angle (FIAA) [8]. Various technical solutions for the implementation of variable FIAA values are considered. There are three groups of such devices:

1) attachments to the high-pressure fuel pump (HPFP) (fuel injection advance coupling);
2) elements embedded in the pump;
3) electronically controlled nozzles and pump nozzles.

The use of FIAA control means allows the use of optimal regulation characteristics, at which given power, economic and environmental characteristics of the engine are achieved.

Fig. 2 presents the basic FIAA characteristics developed by some foreign firms. The plots are constructed in the form of the dependence of the injection start angle φ_{is} on the rotational speed n and the torque M_e. Numerical values are given in relative values.

The basic FIAA characteristics are formed by the microprocessor of the automatic control system for diesel engines with structurally different combustion chambers and high-pressure fuel systems. The optimal FIAA values are selected depending on the purpose of the diesel, taking into account the forcing degree of operating modes and design features.

To intensify the fuel supply process and the workflow of a high-speed diesel engine [9], before starting, the initial pressure in the fuel injection system is increased. Oscillograms of the first two cycles with a preliminary increase in the fuel pressure to P_{st1}=8 MPa are presented in Fig. 3. At the same time, in the second cycle, the residual pressure remains at the level of P_{st2}=3 MPa. In both successive cycles, the average indicator pressure increases, that is, the acceleration intensity increases and the starting characteristics improve.

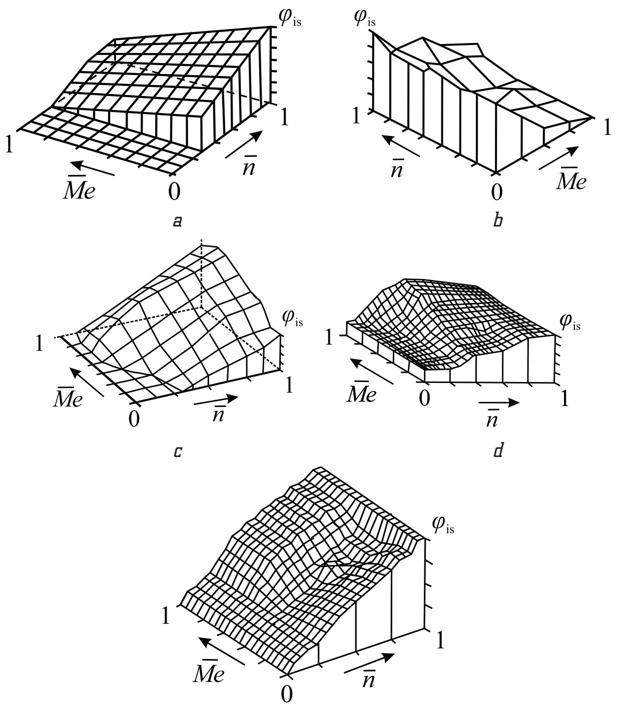

Fig. 2. Basic characteristics of fuel injection advance angle φ_{is} for high-speed diesel engines: *a* – forced diesel with single combustion chamber; *b, c* – diesel engines with pre-chamber mixture formation and a distribution HPFP; *d* – accelerated diesel with in-line HPFP; *e* – vortex chamber diesel

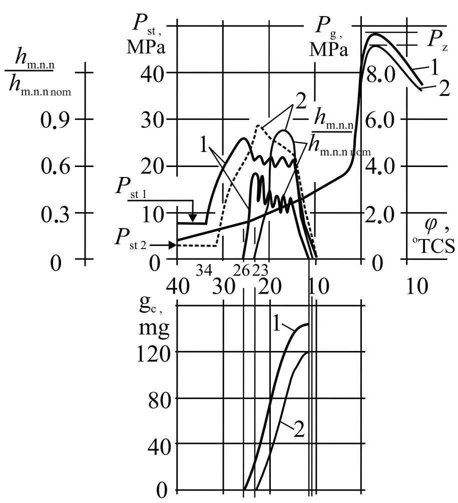

Fig. 3. Oscillogram of the first two start cycles of the D240 diesel (Belarus) after creating an increased initial pressure before the first injection cycle

As a result of tests of the high-speed diesel D240 (4Ч11/12,5) at low ambient temperatures, the obtained FIAA value obtained [10] ensures the minimum start time (Fig. 4).

In [11], the group of authors considers a method for increasing the residual (initial) pressure in the fuel injection system by bypassing part of the fuel from the high pressure line on an additional plunger stroke.

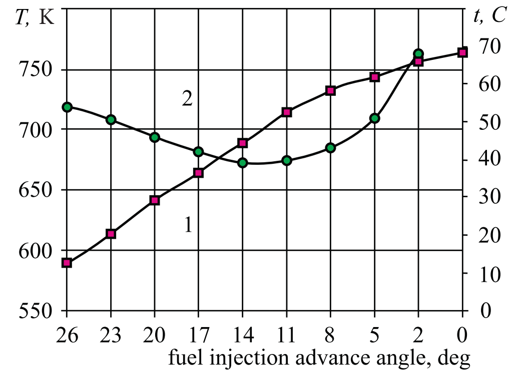

Fig. 4. Temperature dependence in the diesel cylinder at the compression stroke and the duration of cold engine start on the fuel injection advance angle (ambient air temperature 0 °C): 1 – engine cylinder temperature; 2 – start duration

In the study of the dynamic characteristics of the power quality management system in [12], the following dependence of the fuel cycle in the transient regime is proposed:

$$g_{ck}^{n} = g_{ck} + \alpha_c \cdot V_i \cdot \left(P_{rk-1} - P_{rk}\right),$$

where g_{ck} – cyclic fuel supply of the k-th steady-state cycle; α_c – the compressibility factor of the fuel; V_i – the volume of the injection pipeline; P_{rk-1}, P_{rk} – residual pressures in $(k-1)$ and k-th cycles. It is assumed that they immediately follow the position of the rack of the fuel pump and rotational speed.

It is interesting to note the results of studies to improve the dynamic qualities of a 6ЧН15/18 diesel engine (Russia) [13]. Under the condition of increasing the initial pressure in the injection system, a reduction in the engine acceleration time is obtained by 44 %.

The presented review of studies on the transient modes of diesel engines characterizes a significant influence on their development of fuel delivery parameters. So, it is established that the important factors are the injection advance angle and the initial fuel pressure.

At the same time, the obtained data do not contain information on the course of the processes and the essential parameters of fuel injection. The materials published in this paper present the results of research in this direction.

5. Methods of research

The high-pressure fuel system of the ship's medium-speed diesel engine 6ЧН25/34 (Ukraine) is investigated. The composition of the system is traditional:

- closed-type nozzle with a sprayer 9x0.35 mm;
- spool-type injection HPFP, the diameter and stroke of the plunger is 16 mm;
- high pressure fuel pipe with a length of 0.9 m with a diameter of 9 mm and 3 mm (external and internal, respectively).

The study is conducted on a non-motorized bench [5], which provides a stepless change in rotational speed, other operating and adjustment parameters.

In the process of preparing experimental studies, a unique measuring system was created at the Department of Marine Power Plants of the National University «Odessa Maritime Academy» (Ukraine) for recording processes in diesel fuel injection systems. As measuring transducers,

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strain gauges, inductive and photosensors, also developed at the department of ship power plants, were used.

The measuring system (hardware-software complex), united by the common name «strain-gauge station» (SGS), includes the following functional blocks, presented in Fig. 5:

– personal computer (PC);
– LTR-U-1 measuring device (Russia);
– switching unit and amplifiers;
– software package.

is developed. The functional diagram of the complex is shown in Fig. 7.

The complex operates under the control of the ReikaXP2 program installed on a PC. The program interface allows to set the parameters of the cyclogram (displacement law) of the rack manually or by loading the source data from the file, as well as to test the performance of the system in a step-by-step mode of rack displacement at low and high speeds.

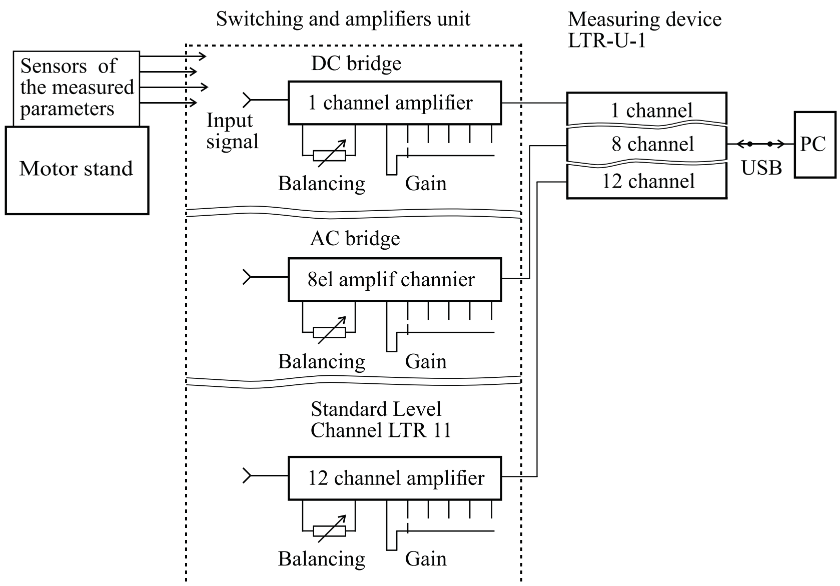

Fig. 5. The functional diagram of the strain-gauge station

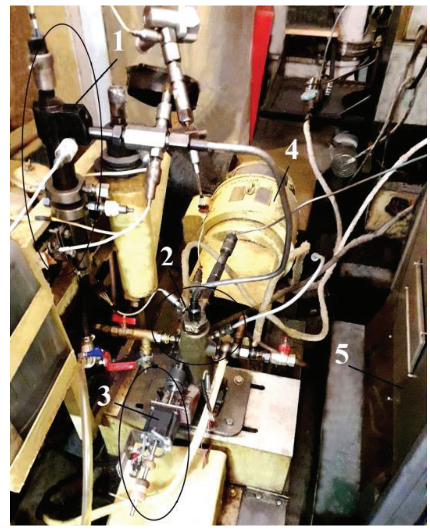

Fig. 6. Fuel injection system with sensors on non-motorized stand: 1 – nozzle; 2 – HPFP; 3 – device that controls the displacement of the fuel pump rack; 4 – electric motor; 5 – motor control station

To ensure the operation of the LTR-U-1 measuring device, which is part of the strain gauge, a switching unit and amplifiers were developed. This unit is designed to provide power and amplification of signals from strain gauges included in the half bridge circuit and general purpose sensors (rotation sensors, photo sensors, etc.).

SGS provides registration of the following parameters of the injection process and working devices of the stand:

– fuel pressure;
– displacement of work items and rotation angles of rotating parts;
– various kinds of signals in the range of ±10 V.

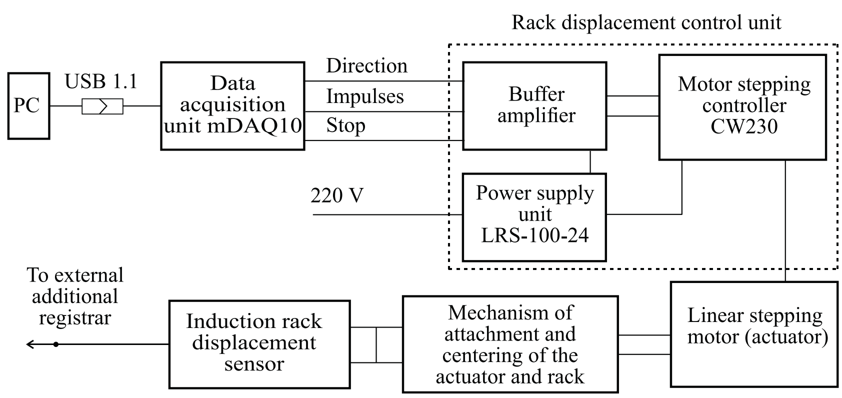

Fig. 7. Functional diagram of the operation of the software and hardware complex for controlling the HPFP rack position

SGS operation control is provided through the joint work of two programs:

– LTRServer, organizing data reception and transmission of PC commands to the LTR-U-1 measuring device via USB interface;
– LGraph package, adapted to the conditions of use in the SGS, allowing to visually adjust some SGS parameters, as well as display on the screen the processes of tuning, receiving and recording data.

A general view of a non-motorized stand with a fuel supply system equipped with sensors of the measuring system is shown in the photographs of Fig. 6.

In addition, for the non-motorized stand, a software-hardware complex for controlling the HPFP rack position

The rack displacement law in the experimental conditions is stepwise. The algorithm of sequential displacement and the time spent by the rack in each position is specified in the test program file. The duration of the experience and the combination of stopping points are not limited.

The executive device of the rack displacement control system is a linear stepping motor (actuator) of SM57HT56-2804TL type (China). The actuator is a combination of a stepping motor and a helical gear made in a single unit. Rotation of the engine rotor of the engine at a certain angle leads to proportional linear displacement of the screw.

The main characteristics of the actuator:

– step (angle of rotation) 1.8° (in full step mode);
– screw pitch 8 mm;

– the maximum displacement speed of the actuator shaft 0.4 m/s (without load).

A general view of the control unit for the fuel pump rack on the non-motorized stand is shown in Fig. 8, a fuel injector with measuring sensors in Fig. 9, and the measuring complex in Fig. 10.

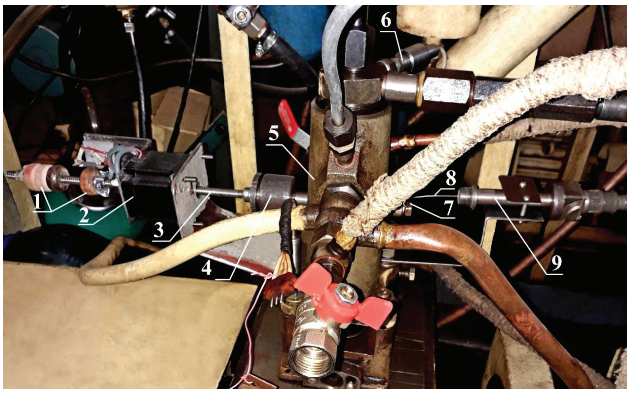

Fig. 8. The control unit of the HPFP rack:
1 – displacement limiter discs; 2 – stepping motor; 3 – actuator shaft; 4 – centering mechanism; 5 – fuel pump; 6 – pressure sensor in the HPFP pump; 7 – rod mounting; 8 – inductive sensor rod; 9 – inductive displacement sensor of HPFP rack

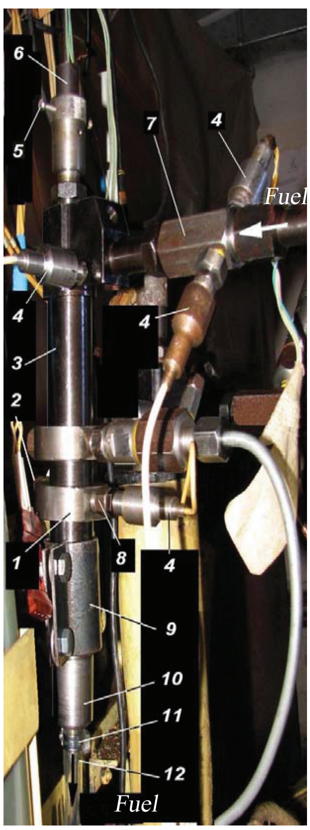

Fig. 9. Installation of sensors on the nozzle:
1 – mounting ring; 2 – pressure bolt; 3 – nozzle assembly; 4 – pressure sensors (4 pcs.); 5 – screw for mounting the needle lift sensor; 6 – needle lift sensor; 7, 8 – adapters for pressure sensors; 9 – nozzle mounting clamp; 10 – muffler anchor; 11 – clamp; 12 – drain tube

Data acquisition microsystem m-DAQ10 (Ukraine) with USB 1.1 interface contains 8 channels of analog-digital conversion, 2 channels of digital-analog conversion. One of the discrete channels can be used as a counter input, and the other as an external trigger for analog-to-digital converter or synchronization. At the pins of the external connector there are also supply voltages of +5 V and ±15 V.

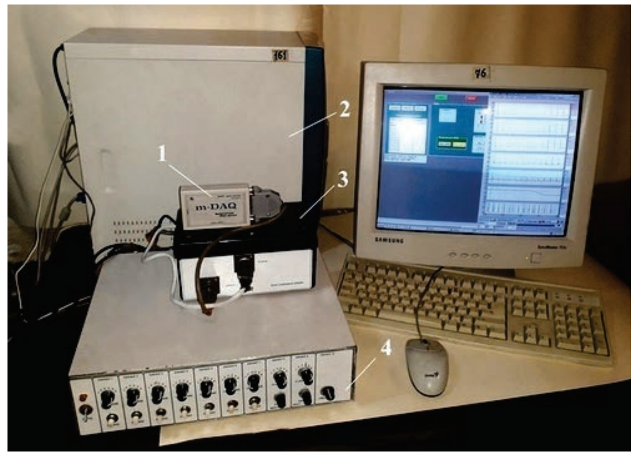

Fig. 10. General view of the measuring complex of the non-motorized stand: 1 – data acquisition microsystem m-DAQ10; 2 – personal computer system unit; 3 – control unit of the rack displacement (actuator); 4 – «strain gauge» system (SGS)

The software for m-DAQ10 contains a dynamic-link library (DLL) driver and examples of working with it, the LLB file extension for the LabVIEW graphical programming environment, and a number of virtual instruments – «oscilloscope», «spectrum analyzer», «frequency meter» and «voltmeter».

6. Research results

During the experimental research, the following parameters were recorded:

- fuel pressure in the fitting of the fuel pump p_p;
- fuel pressure at the inlet to the nozzle of the $p_{n.i.}$;
- pressure in the fuel channel of the nozzle $p_{n.c}$;
- the course of the needle of the dispenser (nozzle) z;
- rotational speed of the camshaft p_c;
- fixed the angle of rotation of the cam shaft φ;
- time t;
- fuel pump rack displacement m_r;
- the test needle tightening was 70 bar.

Pump rack displacement was specified in the source data file for the control program ReikaXP2.exe. After launching ReikaXP2.exe, an image (working window) will appear on the monitor screen. In the working window, four areas are highlighted in Fig. 11:

- the first main area is dark gray. It contains three buttons START, EXIT, HELP and the other three areas;
- the second area is a cyclogram of the rack displacement;
- the third area is the rack;
- the fourth area is the information line.

The program of the experiment and the measurement results are presented in Table 1.

The tests were carried out in the following sequence. After starting the stand, the rotational speed of the cam shaft n_c was set to 250 rpm. With the stabilization of the rotational speed, the LGraph program was launched, which displayed on the screen the processes of setting, receiving and recording these fuel supply parameters. At the same time, the displacement control module of the fuel pump rack ReikaXP was activated. At the end of the experiment program (the ReikaXP stop), with a fixed final rack exit m_r and stabilization of the rotational speed, recording of the fuel supply system parameters was stopped.

As a result of waveform processing, the graphs in Fig. 12 are constructed. Pressure curves p_p, $p_{n.i}$, $p_{n.c}$, camshaft rotation angle φ_c, camshaft rotation speed n_c, HPFP rack displacement m_r are plotted depending on the time since the start of recording and the number of cycles. Stages of rack displacement are marked with numbers I–V.

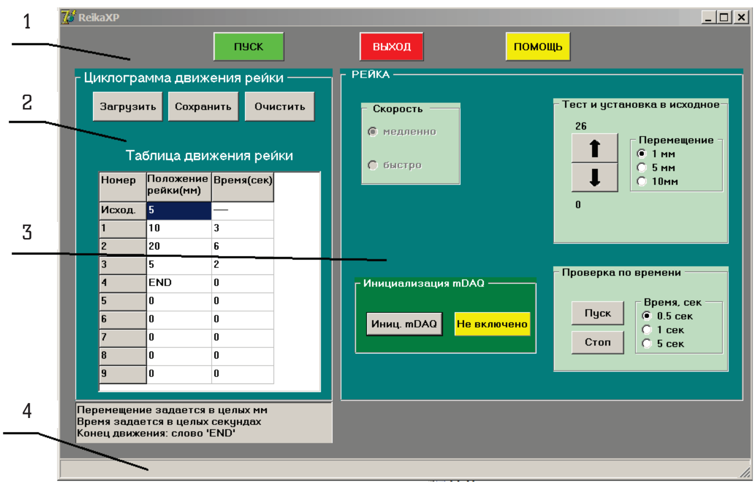

Fig. 11. Window of the control program ReikaXP2.exe: 1 – the main area; 2 – area cyclogram of the rack displacement; 3 – rack area; 4 – information line area

As follows from the graphs (Fig. 12), the duration of the experiment was 44 s, 80 injection cycles and five areas of the FPHP rack displacement. At each area of the pump injection rack displacement, there was one injection cycle occurring during the rack displacement. Characteristics of the HPFP rack displacement across the areas are presented in Table 1.

It is worth paying attention to the fact that the rack displacement speed in different areas is somewhat different. This difference is relatively small, a maximum of 4.37 mm/s and does not exceed 10 %. The likely reason for the difference in rack displacement speed is the difference in resistance to its displacement at the moment of the start. The latter is associated with the HPFP operation phase. With high fuel pressure, the resistance to rotation of the plunger naturally increases, which reduces the rack displacement speed.

Oscillograms of successive injection cycles during the rack displacement along the areas and positions of the HPFP rack are shown in Fig. 13.

Table 1

Characteristics of the HPFP rack displacement in the simulation of the transient process

Area and position of rack	Distance traveled by rack, mm	Time of rack displacement, s	Rack speed, mm/s	Cycle number at the end of the rack displacement
I – 5–25	20	0.44	45.49	5
II – 25–10	15	0.309	48.54	19
III – 10–20	10	0.2259	44.27	32
IV – 20–15	5	0.1085	46.08	45
V – 15–05	10	0.2264	44.17	58

Area I (Fig. 13) shows combined oscillograms of pressure in the nozzle channel $p_{n.c}$ and the injection angle φ_c of successive cycles 4, 5, 6. The HPFP rack is in the initial position, extended to the 5 mm mark, the cam shaft rotation frequency n_c nominal 250 rpm The nozzle pressure $p_{n.c}$ of the channel to the last fourth injection cycle of the steady-state mode before the slat displacement was 216 bar, and the injection angle φ_c=10.0 TDS.

The transient mode in the first area of the displacement is characterized by the following parameters: the rack is shifted to the mark of 25 mm, with the distance of 20 mm covered in 0.44 s at a speed of 45.5 mm/s.

At the time of the displacement accounts for the fifth cycle of injection. Its parameters: pressure $p_{n.c}$=364 bar, φ_c=14.0 TDS. The first injection after stopping the slats (the sixth in terms of the total numbering of cycles) had the parameters of the steady state immediately: $p_{n.c}$=474 bar and φ_c=19.5 TDS.

As indicated above, in the considered (first) area, the time for moving the slats in the range m_r=5–25 mm was 0.44 s at a speed of 45.5 mm/s. This gap corresponds to the full working range. Cam shaft speed was close to nominal. Taking the position of the intermediate during the rack displacement of the fifth injection cycle close to the middle of the range, let's obtain the formation time of the next injection cycle no more than 0.22 s. The characteristics of the intermediate cycle also occupy a middle position.

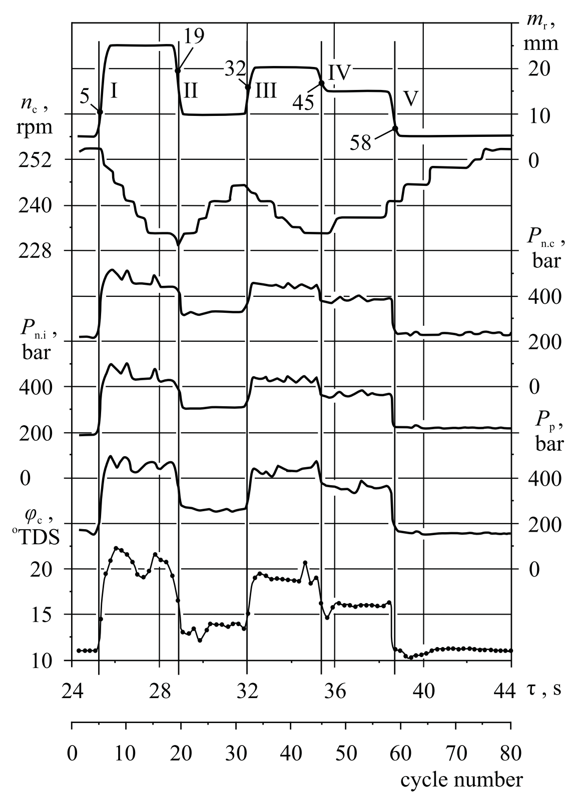

Fig. 12. Parameters of fuel supply on the modes of load characteristics during dynamic tests: areas and positions of the rack: I – 5–25 mm; II – 25–10 mm; III – 10–20 mm; IV – 20–15 mm; V – 15–05 mm; 5, 19, 32, 45, 58 – numbers of cycles when moving the staff

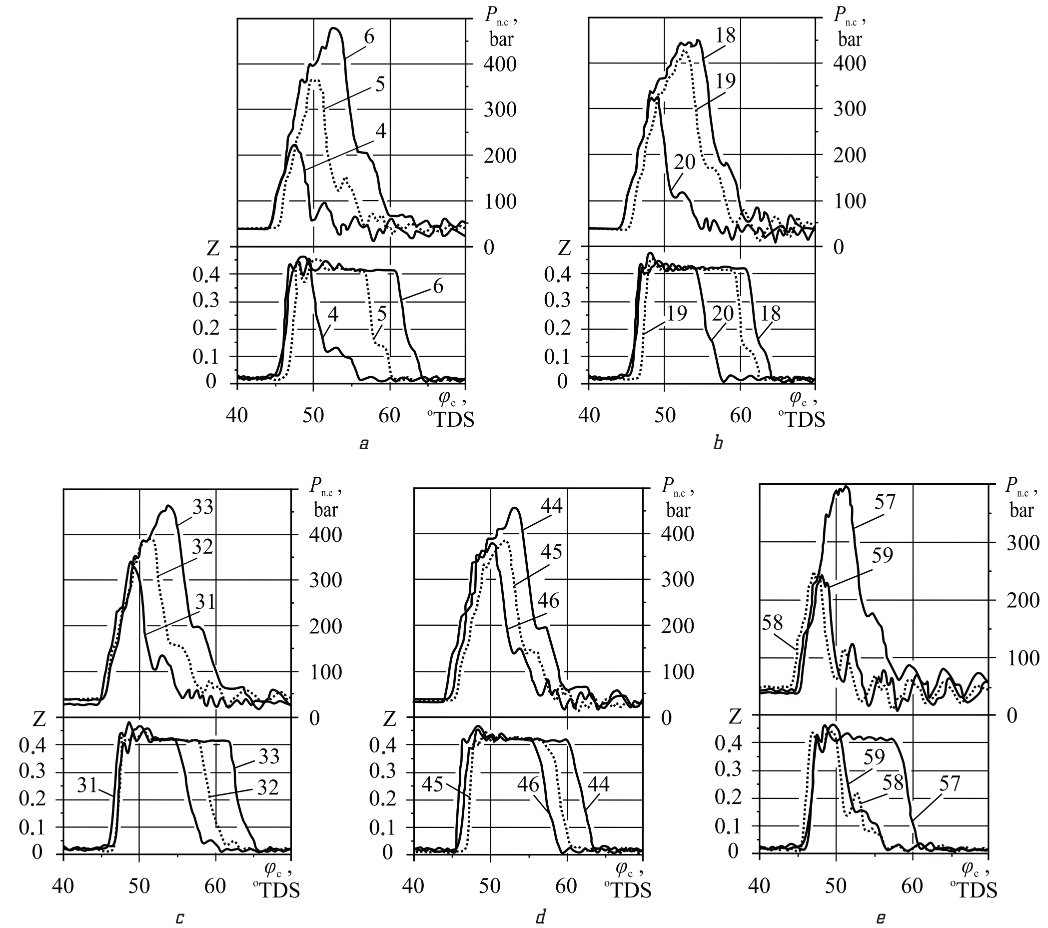

Fig. 13. Combined oscillograms of fuel feed in the areas of load characteristics: - - - cycles 5, 19, 32, 45, 58 – rack displacement; —— cycles 4, 6, 18, 20, 31, 33, 44, 46, 57, 58 – the rack is stable; *a* – I area, m_r=5–25 mm; *b* – II area, m_r=25–10 mm; *c* – III area, m_r=10–20 mm; *d* – IV area, m_r=20–15 mm; *e* – V area, m_r=15–5 mm

Other areas of the load characteristic have the same order of temporal parameters. Consequently, in the experimental conditions, the fuel feed parameters changed simultaneously with the rack displacement.

The fuel injection parameters in the I–V areas of the rack displacement are summarized in Table 2.

Table 2

The parameters of the load characteristics in dynamic tests

Transient regime	Cycle number	p_p, bar	$p_{n.i}$, bar	$p_{n.c}$, bar	φ_c°, TDS	p_{st}, bar	Rack position, m_r, mm	Rotation frequency, *n*, rpm
I	4	152	190	216	10.0	33.3	5	255
	5	284	349	364	14.0	35.9	10.3	255
	6	445	457	474	19.5	33.7	25	250
II	18	469	427	441	19.3	37.6	25	232
	19	388	403	425	16.0	34.8	19.3	230
	20	271	304	316	13	32.4	10	232
III	31	259	314	334	13.3	22.7	10	245
	32	377	375	387	15.2	33.2	15.9	244
	33	442	444	459	19.1	37.8	20	243
IV	44	475	442	450	18.6	36.5	20	233
	45	379	364	376	14.9	37.2	17.1	233
	46	367	361	376	14.6	30.7	15	233
V	57	356	369	390	16.4	31.5	15	241
	58	183	228	251	11.2	45.7	6.9	241
	59	162	222	232	10.6	35.7	5	241

Graphic representation of the obtained load characteristics, constructed in accordance with the data in Table 2, is shown in Fig. 14, *a*, *b*. Its course reflects the growth of all parameters of fuel supply with an increase in the rack exit m_r.

Visual analysis of the distribution of experimental points in the graphs of Fig. 14 indicates the correct representation of the existing dependencies by the approximating curves. For a statistical evaluation of the reliability of experimental data, it is advisable to use the standard deviations of the parameters in absolute and relative values, related to the approximating values represented by the corresponding curve.

To estimate the deviation of the experimental values of the fuel supply parameters from the approximating curve for different positions of the HPFP rack (Fig. 14, *a, b*), let's use the formulas:

$$\sigma = \sqrt{\frac{\sum (y_{ex} - y_{app})^2}{n}},$$

$$\delta = \frac{\sigma}{y_{av}} \cdot 100\ \%,$$

where σ, δ – the absolute and relative standard deviation; y_{ex} – the experimental values of the parameters of the fuel injection process of the corresponding area; y_{app} – the coordinate of the approximating curve in the corresponding area;

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y_{av} – the average value of the process parameters in the corresponding area; n – the total sample size.

As a result, the following values are obtained: for $p_{n.i}$, δ=2.7 %; for $p_{n.c}$ δ=2.6 %; for p_p δ=2.9 %; for φ_c δ=3 %.

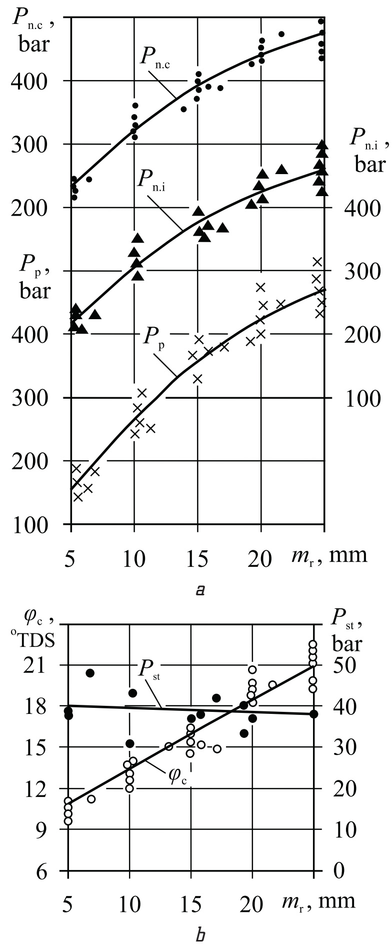

Fig. 14. The dependence of the fuel supply parameter on the HPFP rack position in a dynamic mode: *a* – for $p_{n.c}$, $p_{n.}$, p_p; *b* – for p_{st}, φ_c

Load characteristics of the fuel supply system, obtained in a dynamic mode, is presented in Fig. 14, *a*, *b*. The numerical values of the parameters, as indicated above, are given in Table 2.

For $p_{n.c}$, $p_{n.i.}$, p_p, the test points are grouped in five areas corresponding to the steps of rack displacement (Fig. 14, *a*). Similar areas of values of injection angles φ_c are presented in Fig. 14, *b*.

With a minimum rack exit m_r=5 mm, the fuel pressure φ_c varies from 216 to 222 bar with an average value of 219 bar. The corresponding value $p_{n.i}$ is from 10 to 11 °TDS (on average 10.75°TDS). At the maximum m_r=25 mm, the $p_{n.c}$ range is 474–516 bar, with an average of 470 bar. The injection angle φ_c=19.5–22 °TDS, and the average value is 20.64 °TDS.

The plot of initial pressure P versus rack movement is shown in Fig. 14, *b*. Its average value for all values seems to be almost horizontal line, corresponding to 40 bar, with a relatively wide range of variation of individual values: from 22.7 to 45.7 bar.

In the first area of the record (Fig. 13, *a*), the rack is shown to move from the minimum position to the full feed position.

The front of the curves is the same in shape of the common areas of pressure in the channel and the movement of the nozzle needle. Some shift in the rotation angle is irregular and can be attributed to the inaccuracy of the representation of this parameter. At the same time, this offset improves the ability to match curves.

The pressure reduction area (the tracking edge of the curves) contains on all three oscillograms a short-term decrease in the rate of pressure drop. In this regard, it is possible to talk about the similarity of processes. Moreover, on oscillograms 5, 6 (Fig. 13, *a*) an oscillatory process develops in these areas.

The nature of the waveform displacement of the nozzle needle corresponds to the change in fuel pressure in the nozzle.

In all three cases, the pressure is enough to clearly lift the needle. Attachment happens in different ways. When the rack exit to m_r=25 mm, the fit, as well as the lift, is clear. For the initial value m_r=5 mm and the intermediate value, the needle stroke repeats the nature of the change in fuel pressure and occurs with a delay in the middle part of the needle displacement.

The performed analysis is also characteristic of other parts of the recording of injection processes (Fig. 13, *b*–*d*). In this case, the laws are preserved for moving the rack both upwards and downwards.

7. SWOT analysis of research results

Strengths. The developed method of dynamic testing of injection systems in order to build their characteristics has the following features. This method allows to quickly, in the shortest possible time, build the dependence of the fuel supply parameters on the determining operational factors. These include the rotational speed and the position of the control unit for the quantity of the cycle feed – the exit of the rack of the high-pressure fuel pump. In particular, the recording of the load characteristics with five fixed modes for the ship's medium-speed diesel engine is made within 44 s. At the same time, variable modes that are of great importance in the operation of diesel engines for various purposes are investigated.

Non-motorized bench tests in a dynamic mode can be used to obtain the load characteristics of diesel fuel injection systems, which significantly reduce the time of experiments and increases the reliability of the results.

Weaknesses. The disadvantage of the proposed method is the need to implement the hardware and software developed in this research and the electromechanical complex for automatic control and implementation of test modes.

Opportunities. Opportunities and possibilities of using the research results are determined by the area of application of the equipment in which the fuel injection processes are carried out. Such equipment is diesel engines for various purposes. They are widely used in various industries and transport in all countries of the world. This corresponds to the possible scope of application of research results. Estimation of possible profit at this stage is difficult because of the uncertainty of a significant number of determining factors.

Threats. Testing (research) adjustment of the components (elements) of the fuel system is carried out in laboratory conditions with further installation on the engine. During operation, monitoring of the technical condition requires additional collection of information on hydrodynamic processes, and this will lead to the installation of additional sensors.

Full analogues of this object are not known. The closest analogues solve the specified problems in static conditions by means of separate tests on the modes of load characteristics and on transient modes. The proposed method reduces costs and increases the data reliability.

8. Conclusions

1. For carrying out bench dynamic tests of the fuel supply system of a ship's medium-speed diesel engine in the load characteristic mode, software-hardware controls of the modes, recording and processing of fuel injection parameters are created. ReikaXP program provides the implementation of the experiment plan under the control of a personal computer. When testing implemented stepwise rack displacement in the entire working range with predetermined periods of being in each position. The rack displacement in accordance with the test program is provided by an electromechanical complex designed for conducting experiments.

As a result of the experiment, the loading characteristic of the injection system is constructed with five fixed positions of the HPFP rack. In the investigated range of the rack positions, covering all operating modes m_r=25–5 mm, the main parameters of the fuel supply are as follows: $p_{n.c}$=474–232 bar; $p_{n.i}$=457–222 bar; p_p=445–162 bar.

2. The solution of the problem of determining the parameters of transients is provided by analyzing the characteristics of the HPFP rack movement and fuel supply processes. The transition time of the rack does not exceed 0.44 s, and for changing (setting) the injection process is no more than 0.22 s. It can be assumed that the process of fuel supply in real conditions of transient regimes follows the provisions of the HPFP rack.

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