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DESIGN SPECIFICS OF A BUILT-IN DIAGNOSTIC SYSTEM FOR HYDRAULIC MACHINES

The basis for obtaining information about the object of diagnosis is technical diagnostic tools, which involve measuring operations of various parameters, the totality of which is the basis of the diagnostic process. Diagnostic tools are divided into external, portable (mobile) and built-in. Built-in technical diagnostic tools are considered. The built-in diagnostic system (BDS) is an autonomous complex for automatic checking of the degree of operability and serviceability of units and the hydraulic drive as a whole, which allows, within limited limits, to localize some faults based on the results of monitoring diagnostic and functional parameters in operational or special test modes, and the diagnostic results can be presented to the operator or accumulated for further processing. Compared to other built-in diagnostic tools, BDSs are the most complex and relatively new devices. They are in the process of development, prototyping, and experimental research. A set of diagnostic equipment was designed, namely: designing a unit of measuring instrumentation; designing a load device for diagnosing pumps and taking load characteristics directly at the facility. The designed set of diagnostic devices is used as an integrated diagnostic system (due to built-in sensors), as well as a separate diagnostic complex due to the ability to connect external sensors. The values of the diagnostic parameters measured by this complex can be recorded on an internal memory card or transferred via wireless Bluetooth to a PC or Android device (smartphone, tablet) for further processing. A study was also carried out to assess the strength of the hydrotester body using a computational and analytical method (using the finite element method in the Ansys Static Structural environment), which is equivalent to full-scale testing in terms of boundary conditions and achievable results. Based on the calculation results, it is possible to assert that the choice of material and structural dimensions of the designed device were chosen rationally.

Keywords: technical diagnostics, hydraulic tester, measuring instrumentation unit, load device, pressure, flow rate, fluid temperature.

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ОСОБЛИВОСТІ ПРОЄКТУВАННЯ ВБУДОВАНОЇ СИСТЕМИ ДІАГНОСТУВАННЯ ГІДРАВЛІЧНИХ МАШИН

Основою отримання інформації про об'єкт діагностування є засоби технічного діагностування, при цьому передбачається проведення операцій вимірювання різних параметрів, сукупність яких є основою процесу діагностування. Засоби діагностування поділяють на зовнішні, переносні (пересувні) та вбудовані. Розглянуто вбудовані засоби технічного діагностування. Вбудована система діагностування (ВСД) є автономним комплексом для автоматичної перевірки ступеня працездатності та справності агрегатів і гідроприводу в цілому, що дозволяє, в обмежених межах, локалізувати деякі несправності за результатами контролю діагностичних і функціональних параметрів в експлуатаційних або спеціальних тестових режимах, причому результати діагностування можуть бути представлені оператору або накопичуються для подальшої обробки. По відношенню до інших вбудованих засобів діагностування ВСД є найбільш складними та порівняно новими пристроями. Вони перебувають у стадії розробки, макетування та експериментальних досліджень. Було проведено проєктування комплексу діагностичного обладнання, а саме: проєктування блоку вимірювальних приладів; проєктування навантажувального пристрою для діагностики насосів і зняття навантажувальної характеристики безпосередньо на об'єкті. Спроєктований комплект діагностичних пристроїв використовується в якості вбудованої системи діагностування (за рахунок вбудованих датчиків), а також як окремий діагностичний комплекс за рахунок можливості підключення зовнішніх датчиків. Вимірювані цим комплексом значення діагностичних параметрів можуть бути записані на внутрішню карту пам'яті або передані через бездротовий Bluetooth-зв'язок на персональний комп'ютер PC або Android-пристрій (смартфон, планшет) для подальшої обробки. Також було проведено дослідження оцінки міцності корпусу гідротестера розрахунково-аналітичним способом (із застосуванням методу кінцевих елементів в середовищах Ansys Static Structural), що є еквівалентним натурним випробуванням щодо крайових умов та досяжних результатів. За результатом розрахунку можливо стверджувати, що вибір матеріалу і конструктивні розміри спроєктованого приладу були обрані раціонально.

Ключові слова: технічне діагностування, тестер гідравлічний, блок вимірювальних приладів, навантажувальний пристрій, тиск, витрата, температура робочої рідини.

Introduction. The use of technical diagnostics provides a direction for changing not only the technical condition of the hydraulic drive of machines, but also their maintenance and repair system during operation, since technical diagnostics is a prerequisite for the transition to advanced methods of maintenance and repair of hydraulic drives according to their technical condition.

A diagnostic system should be developed at the design stage of hydraulic drives, because only then can the required level of controllability and manufacturability be ensured. When developing diagnostic systems for hydraulic drives, the following main tasks are solved tasks: development of diagnostic algorithms; forecasting changes in their technical condition during operation; selection of diagnostic methods; development of diagnostic tools [1].

The basis for obtaining information about the object of diagnostics is technical diagnostic tools, which involve measuring operations of various parameters, the totality of which is the basis of the diagnostic process [2].

Diagnostic tools are divided into external, portable (mobile) and built-in. A built-in technical diagnostic tool is a diagnostic tool made in a common design with the object of diagnosis [3].

A technical diagnostics system is a set of means and object of diagnostics and, if necessary, performers prepared for diagnostics or performing it in accordance with the rules established by the relevant documentation [4].

Problem statement in a general way. A significant number of vehicles (land, air, water, underground) and technological facilities are equipped with hydraulic drives. The operability of the hydraulic drive largely determines the reliability of the machine as a whole, so assessing the technical condition of hydraulic systems becomes an important task in the facility diagnostics system [5, 6]. Diagnostics of hydraulic drives can largely solve the problem of diagnosing the object as a whole.

In order to prevent failures and accidents, reduce the time and costs associated with fault detection, there is a need to design and operate built-in diagnostic tools for 'hydro' facilities.

The first step towards obtaining individualised information about the hydraulic drive being diagnosed is the use of combinations of instruments connected to the sensors installed in the drive [7] or on-board monitoring systems for mobile machines [8].

The built-in diagnostic system (BDS) is an autonomous complex for automatic checking of the degree of operability and serviceability of units and the hydraulic drive as a whole, which allows, within limited limits, to localise some faults based on the results of monitoring diagnostic and functional parameters in operational or special test modes, and the diagnostic results can be presented to the operator or accumulated for further processing.

The traditional method of on-board diagnostics is to build an algorithm based on the deviation $\Delta Y(t)$ of the measured value $Y(t)$ from its set value $Y_0(t)$. However, this method allows to establish only the values of the controlled parameter outside the permissible limits and does not specify the cause of the system malfunction. It is possible to create a diagnostic system with elements of artificial intelligence [9, 10]. Such a system on the basis of logical analysis of the values of the controlled parameters identifies the faulty element of the hydraulic drive, indicates the way to eliminate the fault and warns about the pre-emergency situation. This reduces the time-consuming processes of installing measuring equipment during adjustment work and finding and locating faulty hydraulic drive elements, and ensures a significant reduction in labour costs for maintenance and repair by eliminating a significant proportion of sudden failures and by having the driver (operator) participate in the elimination of minor faults of the diagnosed object.

Fig. 1 shows a generalised structure diagram of an embedded microprocessor-based diagnostic system. It includes the following functional units: a primary converter unit, a signal normalisation unit, an on-board microprocessor, a control unit and information display facilities. Analogue and digital signals of pressure, flow rate, degree of purification and level of working fluid, temperature of pump body parts, crankshaft speed of the engine (pumps), some auxiliary signals from low-voltage electrical equipment, etc. can be used as the main input information [11].

Promising functions of built-in diagnostic systems for hydraulic drives include:

- searching for faults or their causes with recommendations to the operator for their elimination and further actions;
- checking the degree of operability of individual subsystems of the diagnosed object in a dialogue mode;
- control of diagnosed systems in case of emergency and pre-emergency situations;
- forecasting the resource life of individual units.

It should also be noted that the feasibility of equipping a built-in diagnostic system is determined by the type of mobile machine or process equipment, their mode of operation, the complexity of the drives being diagnosed, and the responsibility and cost of the operations they perform.

Compared to other built-in diagnostic tools, BDSs are the most complex and relatively new devices. They are in the process of development, prototyping and experimental research.

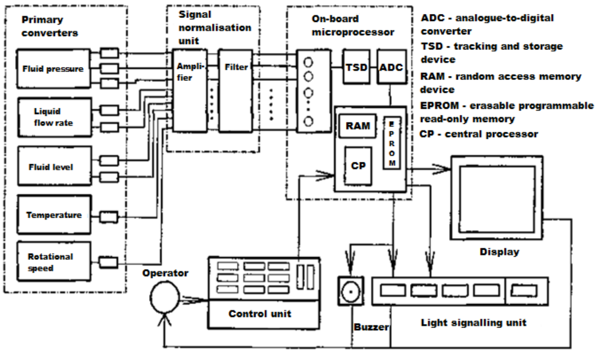


Fig. 1. Structure diagram of the BDS of hydraulic drives

Research Methodology. Quantitative evaluation of diagnostic parameters can be carried out taking into account the provisions of information theory. However, at the first stages, it is advisable to select them on qualitative grounds. One of the criteria may be the attempt to bring the list of faults detected by the built-in diagnostic system as close as possible to the list specified in the classifier of characteristic faults of hydraulic systems of the object being diagnosed. For designed hydraulic drives, such a list can be compiled on the basis of a principle scheme, taking into account the experience of operating similar facilities [12]. Preference should be given to the key parameters that determine the safety of the object to be diagnosed (for example, the pressure in the steering or braking circuits of a mobile machine) and parameters that characterise faults that lead to significant technical and economic losses.

Taking into account the possible options for organising the BDS operation algorithm, the parameters of hydraulic drives can be divided into subgroups according to the following features:

- parameters that determine the safety of the facility;
- parameters for daily inspection (pre-operational inspection);
- parameters for continuous tolerance control;
- auxiliary parameters and control points.

Auxiliary parameters are used to organise the fault finding process. The rationale for using or the significance of an auxiliary parameter can be assessed by the number of elementary algorithms in which it is involved, i.e. the number of faults (and their degree of responsibility) for which this parameter is required to be detected; its exclusion leads to a deterioration in the recognition of many faults.

When selecting the monitored parameters and sensor installation locations, the possibility of measuring the parameter and the design features of the elements of the hydraulic drive being diagnosed should be taken into account.

Based on the above analysis of the design process of an embedded microprocessor-based hydraulic drive diagnostic system, a number of key parameters can be identified that are required in its development:

- number of control points (input signals) and their location at the facility;
- type of input signals;
- nomenclature of sensors;
- level of signals produced by the sensors;
- measurement range for different channels;
- measurement accuracy (of sensors);
- indication discreteness;
- permissible values of measured values;
- microprocessor set, taking into account which the design is carried out;
- memory capacity of RAM and EPROM;
- means of communication with the operator.

These data are part of the terms of reference for the development of the BDS and should be taken into account in the process of formation and refinement.

1. Designing a built-in diagnostic system. It is advisable to design a set of diagnostic equipment for the main range of parameters of modern hydraulic systems of hydrofied equipment [13, 14].

Initial data for design:

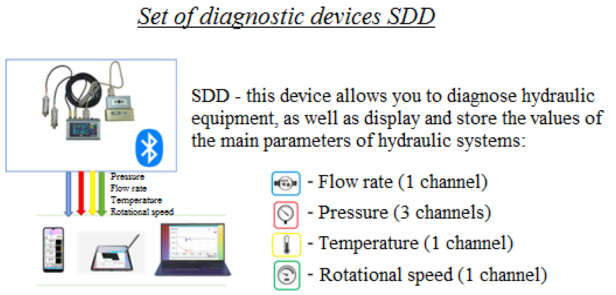
1. the measured flow rate range is from 10 to 200 l/min;
2. pressure measurement range – from 0 to 400 bar;
3. measuring range of working fluid temperature – from 5 to 90°C;
4. measuring range of output shaft rotational speed – from 10 to 10000 min^{-1}.

Based on the initial data, the design consists of two main stages:

- design of the measuring instrumentation unit;
- designing a load device for diagnosing pumps and taking load characteristics directly at the facility.

The hydraulic tester is a handy portable device (Fig. 2) and is designed to diagnose the condition of hydraulic systems by the following parameters [15, 16]:

- fluid flow rate;
- fluid pressure;
- fluid temperature;
- speed of the drive shaft or hydraulic motor shaft.


Set of diagnostic devices SDD

SDD - this device allows you to diagnose hydraulic equipment, as well as display and store the values of the main parameters of hydraulic systems:

- Flow rate (1 channel)
- Pressure (3 channels)
- Temperature (1 channel)
- Rotational speed (1 channel)

Fig. 2. Set of diagnostic devices

The main spheres of application are service and analysis of hydraulic systems.

The tester is based on the ATmega2560 microcontroller. A 3.2" TFT-HX8357 monitor with a resolution of 480x320 pixels is used as a human-machine interface.

The HET-200 has six input channels (three analogue channels – pressure P, P_1, P_2 and three digital channels – flow rate Q, temperature t, rotation speed n) and can display, record and process signals from sensors connected to the device [16].

For operational measurement of the main parameters of the hydraulic system, a single connector with three channels (Q, P, t) is used, to which a block of measuring instruments is connected for simultaneous measurement of the flow, pressure and temperature of the working fluid.

To measure the pressure at different points of the hydraulic system, there are two analogue channels (P_1 and P_2) with separate connectors for connecting pressure sensors. For these sensors, the HET-200 screen can display the measured actual, maximum, minimum pressure values, as well as the difference between the values of channels P_1 and P_2 (P_1–P_2). The maximum and minimum values ($P_{1\min}$, $P_{1\max}$, $P_{2\min}$, $P_{2\max}$) can be reset at any time by pressing the button. The measuring range of the connected sensors is selected in the configuration.

To measure the speed of the drive shaft or hydraulic motor shaft, a separate connector with a digital input (n) is provided, to which a tachometer is connected.

The HET-200 has a built-in real-time clock, which is convenient for processing measurement results. The current date and time are displayed at the top of the screen. Correction of the current date and time is possible in the setup mode.

The measured values can be recorded on the internal memory card or transferred via Bluetooth-wirelessly to a PC or Android-device (smartphone, tablet) for further processing.

The basic set of the hydraulic tester includes:

- hydraulic tester – 1 pc;
- measuring instrumentation unit (to be designed) – 1 pc;
- DB9 (COM) connection cable – 1 pc;
- miniUSB-USB (5V) charging cable – 1 pc;
- USB power supply (5V, 2A) – 1 pc.

The design of the measuring instrumentation unit is shown in Fig. 3.

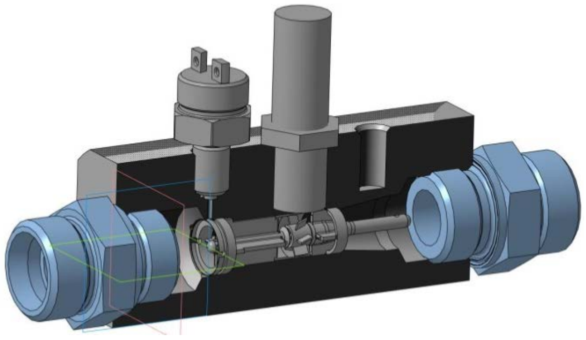


Fig. 3. Design of the measuring instrumentation unit:
1 – body; 2 – turbine; 3 – guide bushing; 4 – inductive turbine speed sensor; 5 – pressure sensor; 6 – temperature sensor installation location; 7 – fittings

The display device has the view shown in Fig. 4.

The general view of the diagnostic equipment set is shown in Fig. 5.

Fig. 4. Device for indicating and recording hydraulic system parameters

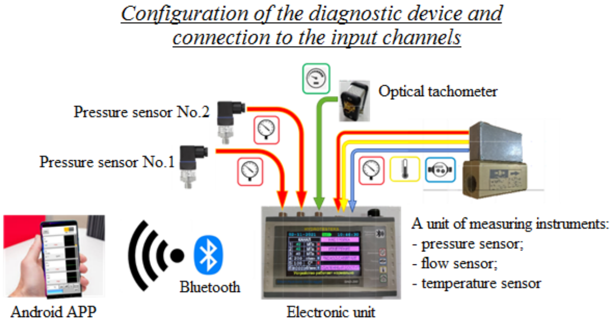


Fig. 5. The diagnostic equipment set

2. Assessment of the strength of the hydrotester body. The aim of the study is to evaluate the strength of the hydrotester body by a computational and analytical method (using the finite element method in the Ansys Static Structural environment), which is equivalent to full-scale testing in terms of boundary conditions and achievable results [17, 18].

The object of research is the body of the measuring instrumentation unit used in the design hydrotester. Test conditions – simulation of full-scale tests by computer calculation using the finite element method in the ANSYS Workbench 2023 R2 environment.

Design model – a solid STEP-model that corresponds exactly to the full-scale sample in terms of dimensions, MCC-characteristics that form the model assembly, as well as materials of their manufacture (tensile strength, yield strength, Poisson's ratio, etc.): Structural Steel (typical characteristics for Steel 3), deformable aluminium alloy of B96 grade – Table 1.

Table 1 – Physical and mechanical properties of the material deformable aluminium alloy grade B96 in the Ansys environment

Density	2850 kg/m^3
Modulus of Elasticity	7400 kg/mm^2
Poisson's ratio	0.36
Young's modulus	76 GPa
Yield strength	550–570 MPa
Tensile strength	480 MPa

At the stage of tensile-compressive elasticity, aluminium alloys have higher relative elongations than steels (Fig. 6).

The body is made of aluminium alloy B96. The appearance of the design model in the ANSYS Workbench software environment is shown in Fig. 7.

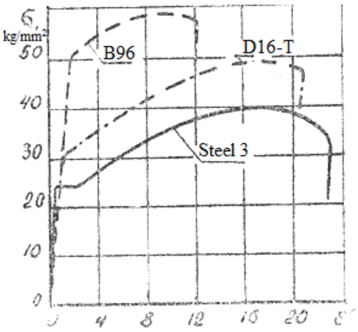


Fig. 6. Tensile-compression diagram of aluminium alloys

At the next stage, the model under study was divided into finite elements (Fig. 8). The total number of finite elements is 21476, which contain 13353 nodes of the tetrahedron type (tetrahedral mesh).

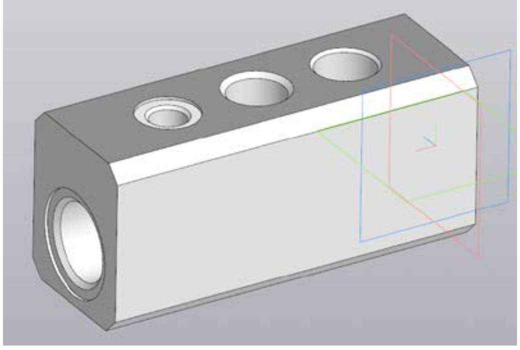


Fig. 7. 3D-model of the body in the ANSYS Workbench environment

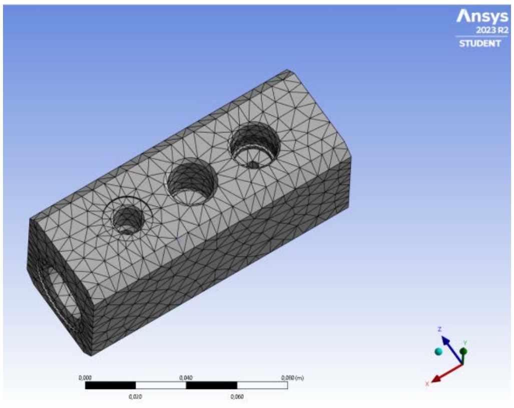


Fig. 8. Breakdown of the model under study into finite elements

Obviously, the model requires the use of displacement constraints, otherwise it will not be statically balanced. Let's set the constraints according to the actual anchoring of the body (Fig. 9) – rigid anchoring at the lower edge of the body (Fixed support).

Let's analyse the design model under the conditions of the working fluid under maximum pressure. In accordance with the operating pressure range of the diagnostic hydraulic equipment, we take the maximum pressure $P_{\max}$ to be 40 MPa. We distribute the pressure over all internal surfaces where the working fluid is located (Fig. 10). The pressure load is applied in stages.

Linear pressure increase to the maximum (40 MPa) in 1 s.

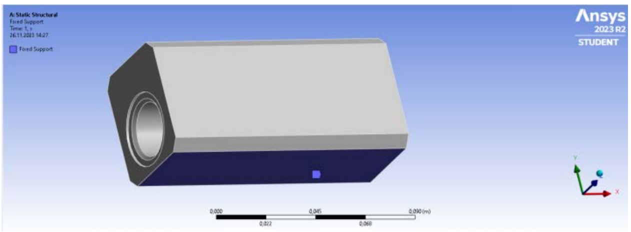


Fig. 9. Formation of boundary conditions for calculation

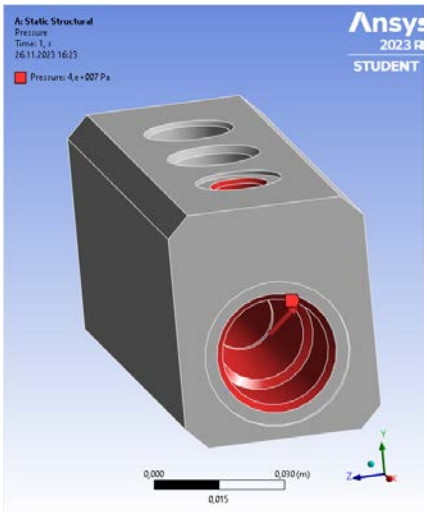


Fig. 10. Scheme of loading with pressure $P_{\max} = 40$ MPa

To familiarise yourself with the results of the calculation, it is advisable to familiarise yourself with the Mises maximum stress criteria, which is based on the Mises-Hencky theory, also known as the theory of shape change energy. In elasticity theory, an infinitesimal volume of material at any point on or inside a solid can be rotated so that only normal stresses remain and all shear stresses are zero. The three remaining normal stresses are called principal stresses: σ_1 – maximum, σ_2 – average, σ_3 – minimum. In this case, the following condition is met: $\sigma_1 > \sigma_2 > \sigma_3$.

For principal stresses σ_1, σ_2, σ_3, the Mises stress is expressed as follows:

$$\sigma_{vonMises} = \{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]/2\}^{1/2}.$$

The theory states that a ductile material begins to fail at the point where the Mises stress becomes equal to the ultimate stress. In most cases, the yield strength is used as the ultimate stress σ_{limit}, so the condition $\sigma_{vonMises} \geq \sigma_{limit}$ must be met. Since our problem does not involve plastic deformations, the research is carried out within the framework of Hooke's law. With a linear relationship between strain and material isotropy, stresses and strains are related by Hooke's law as follows (excluding temperature effects):

$$\varepsilon_x = \frac{1}{E}\left(\sigma_x - \nu\sigma_y - \nu\sigma_z\right), \gamma_{xy} = \frac{1}{G}\tau_{xy};$$

$$\varepsilon_y = \frac{1}{E}\left(-\nu\sigma_x + \sigma_y - \nu\sigma_z\right), \gamma_{xz} = \frac{1}{G}\tau_{xz};$$

$$\varepsilon_z = \frac{1}{E}\left(-\nu\sigma_x - \nu\sigma_y - \sigma_z\right), \gamma_{yz} = \frac{1}{G}\tau_{yz},$$

where $\varepsilon_x, \varepsilon_y, \varepsilon_z$ – linear deformations; E – Young's modulus; G – shear module; $\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ – shear deformations in the relevant planes; ν – Poisson's ratio (shown in Table 1).

The distribution of equivalent stresses (fourth theory of strength) in a part is shown in Fig. 11.

The colour palette corresponding to the numerical stress values in Pa is shown. The maximum equivalent stresses in the part were $\sigma_{\max} = 192$ MPa.

The distribution of total deformations in the part is shown in Fig. 12.

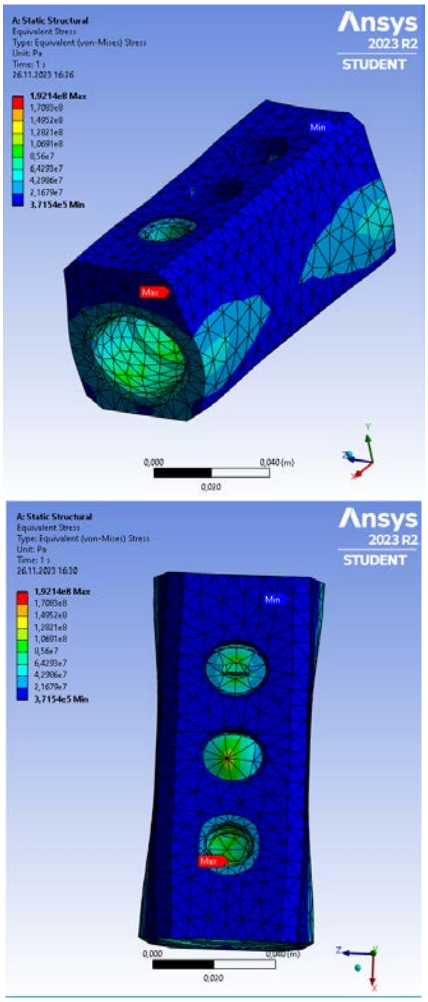


Fig. 11. Equivalent stress distribution palette

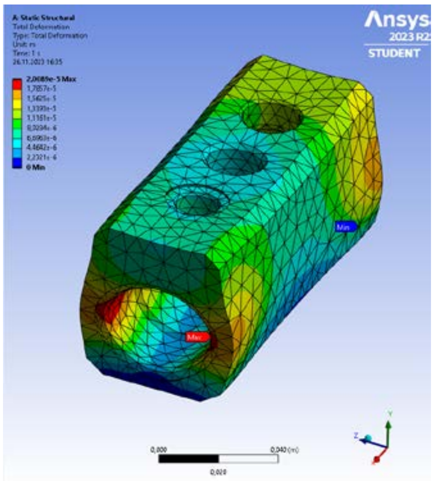


Fig. 12. Total strain distribution palette

The maximum deformation is 0.02 mm in the area of the threaded connection of the fittings.

The value of the minimum safety factor (Fig. 13) at the yield strength is $n_{\min} = 1.5289$, which is sufficient.

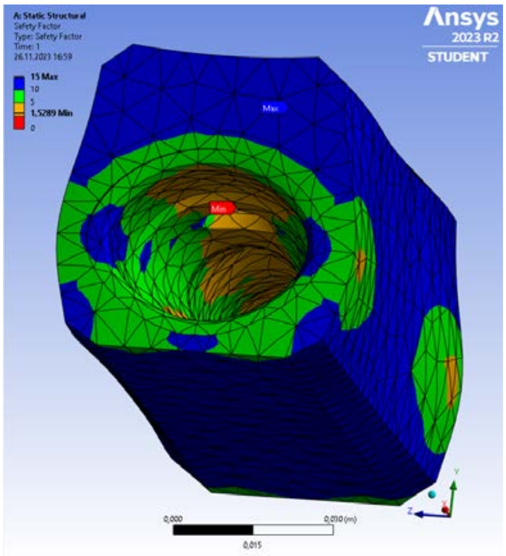


Fig. 13. Safety factor distribution palette

Based on the results of the calculation, it is possible to assert that the choice of material and structural dimensions was correct.

Conclusions. According to the above structural diagram of the built-in microprocessor diagnostic system, a set of diagnostic devices was developed that can be used as a built-in diagnostic system (due to built-in sensors), as well as a separate diagnostic complex due to the possibility of connecting external sensors.

To solve the problems of operational measurement of the main parameters of hydraulic systems, a set of diagnostic equipment was developed for the main range of parameters of modern hydraulic systems, namely the flow range from 10 to 200 l/min, the pressure range from 0 to 400 bar, the temperature range from 5 to 90°C.

A study was also carried out to assess the strength of the hydrotester body using a computational and analytical method (using the finite element method in the Ansys Static Structural environment), which is equivalent to full-scale testing in terms of boundary conditions and achievable results. The calculation results confirm the correct choice of material and structural dimensions, which is also confirmed by hydrostatic testing of the prototype.

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