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Technique of functional unification of adaptive hydraulic drive module capable of load stabilization on the working body of mobile machines[*]

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Методика функциональной унификации адаптивного модуля гидропривода с функцией стабилизации нагрузки на рабочем органе мобильных машин[***]

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Introduction. Issues on the functional unification of the adaptive hydraulic drive module are studied. For the first time, self-adapting mechanisms are considered taking into account adaptive intercommunication of the load control and agreement of motions on the working body of the mobile machines. The work objective is to create and analyze the technique of the functional unification of the adaptive hydraulic drive module. In the furtherance of this goal, a number of tasks are solved. The selection of technical equipment – unified adaptive hydraulic drive modules of the mobile machines – is validated. The methodology and indicators of the module functional unification are described. Intercommunications are considered: direct positive and back negative ones. Their effect on the functional unification property of the adaptive module is shown.

Materials and Methods. For the synthesis and analysis of the functional unification indicators of the adaptive module, a similarity method of the technical systems operation is adopted.

Research Results. Techniques for structural-functional unification of the self-adapting modules are developed. Optional versions of the unified modules modification and proper combinations of hydraulic motors, regulating equipment, and mathematical models of adaptive communications are presented. Criteria and indicators of similarity are proposed. The functional unification of the adaptive intercommunications of the module and different types of the hydraulic motors and fluid throttling elements in the hydraulic system are analyzed. Recommendations for implementing the functional unification under typing and operation (adjustment) of the adaptive module are formulated.

Discussion and Conclusions. The methodology is recommended for the functional unification of the hydraulic self-adapting

Введение. Исследованы вопросы функциональной унификации адаптивного модуля гидропривода. Впервые рассмотрены принципы самоадаптации с учетом внутренних адаптивных связей управления нагрузкой и согласованности движений на рабочем органе мобильных машин.

Цель работы — создание и анализ методики функциональной унификации адаптивного модуля гидропривода. Для достижения поставленной цели решен ряд задач. Обоснован выбор технических устройств — унифицируемых адаптивных модулей гидропривода мобильных машин. Предложены методика и показатели функциональной унификации модуля. Рассмотрены внутренние связи: прямая положительная и обратная отрицательная. Показано их влияние на свойство функциональной унификации адаптивного модуля.

Материалы и методы. Для синтеза и анализа показателей функциональной унификации адаптивного модуля принят метод подобия функционирования технических систем.

Результаты исследования. Разработана методика проведения конструктивно-функциональной унификации модулей с самоадаптацией. Показаны возможные варианты модификации унифицируемых модулей и соответствующие им сочетания гидродвигателей, регулирующей аппаратуры и математических моделей адаптивных связей. Предложены критерии и индикаторы подобия. Выполнен анализ функциональной унификации внутренних адаптивных связей модуля с разными типами гидродвигателей и элементов дросселирования жидкости в гидросистеме. Сформулированы рекомендации проведения функциональной унификации при типизации и эксплуатации (наладке) адаптивного модуля.

Обсуждение и заключения. Методика рекомендована для функциональной унификации гидравлического модуля с

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module. It can be used for the development of unit sizes and under its operation as an independent drive or a hydraulic drive subsystem of a multifunctional or combined machine.

самоадаптацией. Она может использоваться при разработке типоразмеров модуля и в процессе его эксплуатации в качестве автономного привода или подсистемы гидропривода многофункциональной или комбинированной машины.

Keywords: functional unification, typing, hydraulic drive, standard unified self-adapting module, method of operation similarity, mobile machines.

Ключевые слова: функциональная унификация; типизация; гидропривод; типовой унифицированный модуль с самоадаптацией; метод подобия функционирования; мобильные машины.

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Introduction. Multifunctional and combined mobile machines are abundantly used under difficult conditions: in road construction and agricultural work. As a rule, their operation involves manual or hard-programmed control. Thus, it is important to create simple functionally unified drives (modules) of mobile machines capable of adapting to the variable properties of the processed environment [1].

It should be noted that the issues of unification are related to the solution of a number of scientific and practical problems. One of them is the problem of standard sizes of functionally unified products. For its solution, the corresponding means of fundamental [2] and applied [3, 4, 5] mathematics is used. Studies on the adaptive systems of different structures and purposes [6], hydraulic drives of devices with adaptively coordinated movements of the working body taking up stochastic fluctuating loads are carried out [7, 8, 9, 10]. In the framework of this paper, the principle of functional unification in the modular hydraulic drive capable of load self-adaptation is considered. The research and practical testing of such a module is conducted for the first time.

Materials and Methods. A device for drilling rocks with variable properties [11] and a device for processing curved surfaces [12] are accepted as the basic objects of research (Fig. 1, 2).

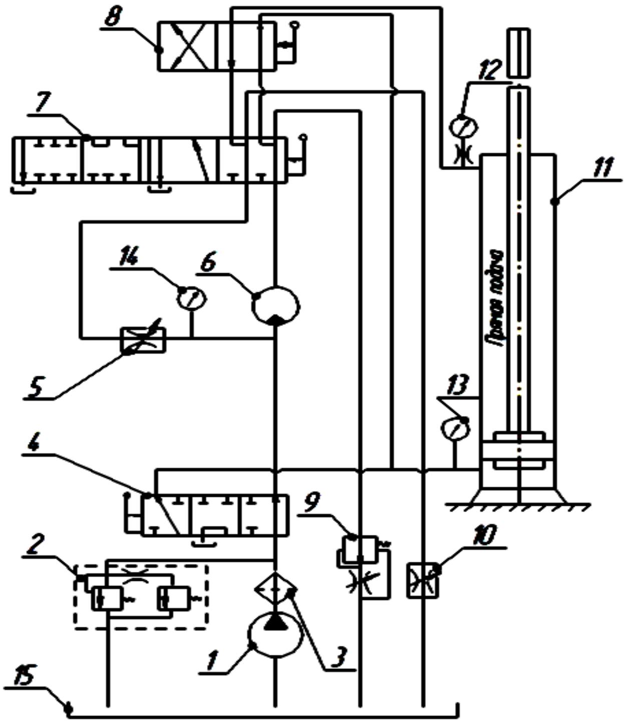

Fig. 1. Schematic diagram of device for drilling rocks with variable properties [3]

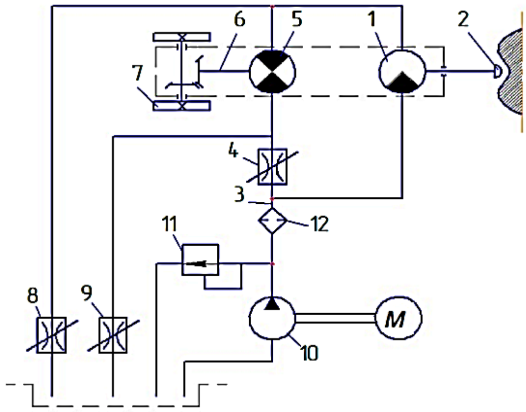

Fig. 2. Schematic diagram of device for processing curved surfaces [2]

The following elements are numbered in the diagrams (for Fig. 2, designations are given in brackets): 1 (10) — fixed displacement hydraulic pump; 2 (11) — safety valve; 3 (12) — filter; 4, 7, 8 — control valves; 5 (4) — choke (mode control); 6 (1) — main motion hydraulic motor; 9 — flow control; 10 — retaining adjustable choke; 11 — feed hydraulic cylinder; 12, 13, 14 — pressure gauges; 15 — tank; (2) — working body; (3) — hydraulic system; (5) — reversible feed motor; (6) — feed motor shaft; (7) — feed mechanism; (8, 9) — adjustable chokes.

The elements of the hydraulic system of these devices (including their modifications [13]) are structurally combined according to the differential scheme.

A hydraulic cylinder (see Fig. 1) or hydraulic motor (see Fig. 2) are additionally included between the return lines of the mode control and the main motion hydraulic motor. Thus, two communications are established: the back negative and the direct positive.

A flow control (see Fig. 1) is on the return line of the hydraulic motor of the main motion of the drilling device under consideration. An adjustable choke (see Fig. 2) is on the return line of the hydraulic motor of the main motion of the device for processing curved surfaces. This is the fundamental difference between these devices.

Such variations of the unified modules allow providing a combination of movements of the working body of the mobile machine: rotation-feed; rotation-rotation; feed-feed [14].

Design differences affect the characteristics of direct positive and back negative communications of the devices, both unified and modular (Table 1, 2).

Table 1

Functional dependences of adaptive communications between the module and the flow control

Types of hydraulic motors	Functions of module adaptive communications	
	Back negative	Direct positive
Hydraulic motor of the main motion — feed hydraulic motor	$\omega_{\text{гп}} = AM_0 - (BM_{\text{сгд}} + CM_{\text{сдп}})$	$\omega_{\text{гп}} = k_1\omega_{\text{гд}}$
Hydraulic motor of the main motion —feed hydraulic cylinder ω	$\omega_{\text{гп}} = AM_0 - (BM_{\text{сгд}} + CM_{\text{сдп}})$	$v_{\text{цп}} = k_2\omega_{\text{гд}}$
Hydraulic cylinder of the main motion — feed hydraulic cylinder	$v_{\text{цп}} = AM_0 - (BM_{\text{сгд}} + CM_{\text{сцп}})$	$v_{\text{цп}} = k_3\, v_{\text{цп}}$

Table 2

Functional dependencies of the adaptive communications of the module with an adjustable throttle

Types of hydraulic motors	Functions of module adaptive communications	
	Back negative	Direct positive
Hydraulic motor of the main motion — feed hydraulic motor	$\omega_{гп} = AM_0 - (BM_{сгд} + CM_{сдп})$	$\omega_{гп} = k_1\omega_{гд} - \mu \frac{f_{др8}}{f_{цп}} \sqrt{\frac{2\Delta P_{др8}}{\rho}}$
Hydraulic motor of the main motion —feed hydraulic cylinder	$\omega_{гп} = AM_0 - (BM_{сгд} + CF_{сдп})$	$v_{цп} = k_2\omega_{гд} - \mu \frac{f_{др8}}{f_{цп}} \sqrt{\frac{2\Delta P_{др8}}{\rho}}$
Hydraulic cylinder of the main motion — feed hydraulic cylinder	$v_{цп} = AM_0 - (BF_{сгд} + CF_{сцп})$	$v_{цп} = k_3 v_{цгд} - \mu \frac{f_{др8}}{f_{цп}} \sqrt{\frac{2\Delta P_{др8}}{\rho}}$

Let us note that the ratio of the velocities of the output elements of hydraulic motors (see Table 2) does not depend on the flow rate through the flow control, since this indicator does not depend on the pressure drop on the device, i.e. $Q_{рп} = const$.

Adaptive communications play a special role at action of working bodies of machines in modes with the required indicators of speed of performance of operations and stability [14]. The discussed above design and functional features of the devices (presence of an adjustable throttle or flow control) allow implementing such communications.

Tables 1 and 2 provide the legend: $v_{цп}$ — rod speed; $f_{цп}$ — cross sectional area of the feed hydraulic cylinder; $\omega_{гд}$ — angular velocity of the hydraulic motor main movement; A, B, C — constant coefficients depending on the moments of inertia, kinematic parameters and efficiency of the units of the main drive and feed drive module; M_0 — the nominal and the calculated total moment of resistance corresponding to the processing without adaptation; $f_{др8}$ — area of flow cross-section of the throttle $Др_8$; $M_{сгд}$, $M_{сдп}$ — the actual moments of resistance taken up respectively by the main drive shaft and the feed shaft; $F_{сгд}$, $F_{сцп}$ — the actual resistance forces, which are taken up respectively by the rod of hydraulic cylinders of main movement and the feed cylinder; $\Delta P_{др8}$ — the pressure differential on the throttle $Др_8$; ρ — density of the working medium in the hydraulic system (oil); k_1, k_2, k_3 — the coefficients of conversion of design features and dimensions of the speeds of movements.

Back negative communication allows stabilizing the actual total moment (force) of the resistance on the working body in the process of the module work. In this case, we automatically compare:

- the actual moment of resistance with the value set by the mode regulator;
- changes in feed rates and the main motion with the sign, reverse to the error signal.

The following are the relevant equations of back communication on accelerations of the shaft of the feed hydraulic motor.

If there is a flow regulator:

$$\varphi_{гп} = \frac{1}{k_{сгп}}\left[-A\,\frac{\pm\frac{d}{dt}\left(B\Delta M^0_{сгд} + C\Delta M^0_{сдп}\right)}{\left(B\Delta M^0_{сгд} + C\Delta M^0_{сдп}\right)^{0,5}}\right]. \quad (1)$$

If there is an adjustable throttle:

$$\varphi_{гп} = -\frac{1}{k_{сгп}}[(A\,\frac{\pm\frac{d}{dt}\left(B\Delta M^0_{сгд} + C\Delta M^0_{сдп}\right)}{\left(B\Delta M^0_{сгд} + C\Delta M^0_{сдп}\right)^{0,5}} +$$

$$+\mu_{др3} f_{др3}\frac{d}{dt}\sqrt{\frac{2(\Delta P^0_{др3} \pm \delta(\Delta P^0_{др3})}{\rho}})]. \quad (2)$$

The methodology of functional unification is determined by its goals and features, as well as the stage of the module life cycle. However, we should note the overall steps of its implementation:

- clarification of the functional purpose and conditions of the unified module operation;
- preliminary data collection within the framework of constructive and functional unification of hydraulic devices of standard and unified module (including single-valuedness conditions; nominal and boundary values of operation parameters, especially pressure drops on hydraulic devices under the conditions of dynamic equilibrium of hydraulic system);
- clarification of the adaptive communication type according to the design features of the modules (in accordance with Tables 1 and 2).

In compliance with the mentioned general provisions, the functional unification of adaptive communications is performed in a certain sequence.

- According to the calculation or by the specification, the passport, we specify the values of working (or maximum) loadings on the working body of the mobile machine with the unified module.

- In relation to the standard module, we determine the functional and design values of the parameters of the hydraulic elements of the unified module. Here we use nomograms, graphs or calculations (for example, by the method of similarity of functioning) [15].

Research Results. When performing unification, the principle of superposition of functions is used.

Let us briefly consider an example of the method of functional unification of hydraulic motors of the module.

The output characteristics of the hydraulic motor and the hydraulic cylinder are angular velocity (rotation frequency) and torque on the shaft of the hydraulic motor, linear speed and force on the rod of the hydraulic cylinder. Functional dependencies that define these characteristics have the following form [16]:

a) for the hydraulic motor

$$\begin{aligned} M_{гм} &= f_1(P_{вх}, q, \beta, J, M_{тр}, \Delta P_{ут}(Q_{ут}, f_{щ}, \rho)), \\ n_{гм} &= f_2(Q, q, \upsilon, E, Q_{ут}(\Delta P_{ут}, f_{щ}, \rho)); \end{aligned} \tag{3}$$

b) for the hydraulic cylinder

$$\begin{aligned} V_{ш} &= f_1(Q, d_{ц}, \delta, \rho, \Delta \mathrm{P}_{ц}, E, V_{v}), \\ F_{ш} &= f_2(\Delta \mathrm{P}_{ц}, \Delta F_{п}, m_{пд}, F_{стр}, \mu, F_{вт}, \beta). \end{aligned} \tag{4}$$

Here $n_{гм}$ — shaft speed; q — volume of oil; Q — flow (supply) of oil; E — elastic modulus; μ — dynamic oil viscosity ρ — density of oil; $P_{вх}$ — inlet pressure; $\Delta P_{ут}$ — differential pressure on leakage element; $Q_{ут}$ — leakage value; $f_{щ}$ — the area of the slit through which passes a leak; J — moment of inertia; β — oil compression coefficient; ; $F_{стр}$, $F_{вт}$ — equivalent force of breakaway and internal friction in the cylinder; r — radius of rotation of the mass; ξ, ν — structural coefficients; $M_{в}$ — shaft torque; $M_{тр}$ — friction torque; $\Delta P_{ц}$ — differential pressure on hydraulic cylinder; $F_{ш}$ —stress on the rod; ΔFп — the difference between the forces on the piston.

When carrying out constructive and functional unification, special criteria of similarity of unification [17] obtained by the dimensional analysis [15] are used.

For a hydraulic motor, the similarity criteria of unification have the form:

$$\begin{aligned} &\pi_n = \frac{n}{Q} f_{ц}^{1,5}; \pi_q = \frac{q}{Q} f_{щ}^{1,5}; \pi_E = \frac{E}{\Delta P}; \pi_\beta = \beta P_{вх}, \\ &\pi_{M_{тр}} = \frac{M_{тр}\rho^3}{P_{вх} J^3}; \pi_{\Delta P} = \frac{\Delta P}{P_{вх}}; {}_j = \frac{f_{ц}\rho^2}{J^2}; \\ &\pi_{Qc} = \frac{Qc\mu^{0,33}}{P_{н}^{0,33} q};\ \pi_{pc} = \frac{\rho\, q^{0,67}}{P_{н}^{0,33}\mu^{0,67}}. \end{aligned} \tag{5}$$

Similarity criteria of unification have certain functional or structural sense, namely: π_n — the criterion of flow kinematic parameters; π_q — the criterion that characterizes the ratio of constructive and consumable (functional) characteristics; π_E — the criterion that characterizes the nominal stiffness of the working fluid; π_μ — the theoretical (indicator) criterion of the shaft torque of the pump; π_β — the criterion of elastic deformation of the working fluid; π_{Mm} — the criterion of friction losses in mates; π_J — the criterion of the loss of inertia hydraulic-mechanical resistance; π_{Q_c} — the criterion of the loss of hydrodynamic resistance of the working fluid; $\pi_{\Delta P_y}$ — the criterion of the loss to overcome the leakage of the working fluid; π_{pc} — the criterion of the loss on the inner (viscous) resistance of the working environment.

Thus, each criterion reflects the essence of one of the properties of the functional unification of the module, and any system of criteria reflects this property generally.

The generalized similarity criteria for unification obtained by combinations of separate criteria are presented in the form of:

$$M_{г} = \frac{\pi_{м}\pi_{P_{в}}\pi_{щ}}{\pi_E \pi_r \pi_y \pi_{N_T} \pi_Q \pi_\rho} \frac{Pq^{0,67} rJN_{тр} Q\rho}{P_{в}\mu E f y};\ n_{г} = \pi_n \pi_q \pi_\nu \pi_E^{-1} \pi_y \frac{Q f_{рэ} f_y^2 E \Delta P_y}{q^2 \nu P \rho Q_y}. \tag{6}$$

Particular similarity indicators of the functional unification of C_i, are obtained from the equations (5) for the unified model and standard modules [15]. In this case, the respective similarity number π_{yi} and π_{mi} for the standard and the unified modules should be equal:

$$\pi_{yi} = \pi_{mi} = idem. \qquad (7)$$

In this example, separate indicators of similarity of functional unification have the following form:

$$1=\frac{C_n}{C_q}C_{f_{\text{ц}}}{}^{1,5}\ ;\ 1=\frac{C_q}{C_q}\ C_{f_{\text{ц}}}{}^{1,5};\ 1=\frac{C_E}{C_{\Delta P}}\ ;\ 1=C_{\beta}C_{P_{\text{вх}}}\ ;\ 1=\frac{C_{M_{\text{тр}}}C_{\rho^3}}{P_{\text{вх}}J^3}; \qquad (8)$$

$$1=\frac{C_{M_{\text{гм}}}\rho^3}{C_{P_{\text{вх}}}C_{J^3}};\ 1=\frac{\Delta P}{P_{\text{вх}}};\ 1=\frac{C_Q C_{\mu^{0,33}}}{P_{\text{н}}^{0,33}q};\ 1=\frac{C_Q}{C_q{}^2}\frac{C_{\Delta P_{\text{гм}}}}{C_{\rho}}.$$

As well as similarity criteria of functional unification, separate indicators can be combined into complexes, obtaining the effect of superposition.

The change of scale of parameters C_i of the unified module in indicators (8) in relation to similar parameters of the indicators of the standard module shall correspond to the condition of equality to 1 [15]. For example, for the output characteristic of $\Delta P_{\text{гм}}$ on the indicator

$$1=\frac{C_Q}{C_q{}^2}\frac{C_{\Delta P_{\text{гм}}}}{C_{\rho}} \qquad (9)$$

you can analyze the functional unification on the pressure drop, the characteristic (working) volume and flow of the hydraulic motor, oil density.

The required standard size of one of the parameters of the unified module is determined by the substitution in (5) and (8) of the known values of the parameters of the standard module hydraulic motor and a priori known (established by technical specifications, etc.) values of the parameters of the unified module.

The features of the procedure of functional unification research depend on the task. When carrying out unification of the module of a new standard size, first, you carry out constructively-functional unification, the choice of standard sizes of elements of the hydraulic system, and then you check their functional compliance to the internal adaptive intercommunications. To solve the first problem, we use particular criteria and indicators of functional unification similarity. To solve the second problem, generalized criteria, indicators, as well as the equations of direct and back adaptive intercommunications are used.

Other objectives of the unification of the adaptive module are: analysis of the causes of violations of functional unification in the process of operation of a single adaptive module, and the study of the effectiveness of functional unification in the modernization of the adaptive module of a hydraulic drive. The method of similarity of functioning of technical systems can also be used [18], [19].

Discussion and Conclusions. The urgency of development and application of the unified hydraulic drive of modular type in mobile machines is proved. This design allows you to adapt the power and kinematic parameters when the working body is exposed to fluctuating loads. The method of carrying out constructive and functional unification of modules with self-adaptation involves the use of mathematical models of adaptive intercommunications. Optional versions of modification of the unified modules with self-adaptation and the corresponding combinations of hydraulic motors, regulating equipment and mathematical models of adaptive intercommunications are shown. An example of the functional unification technique using the method of similarity of technical systems operation is given. The technique is recommended for the study of functional unification in the development of standard sizes and in the operation of the proposed type of module.

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