Improving the Technical Level of Hydraulic Machines, Hydraulic Units and Hydraulic Devices using a Definitive Assessment Criterion at the Design Stage

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ABSTRACT

To date, the assessment of the technical level of individual elements of hydraulic drive systems has been significantly addressed, but most of them were positive-displacement machines. Thus, the development of a criterion which takes into account the maximum number of indicators and hydraulic devices and is based on common methodological principles is an important scientific and technical task for the assessment of the technical level of hydraulic machines, hydraulic units, and hydraulic devices. Based on a systematic analysis of the technical level evaluation indicators of a wide range of hydraulic drive system elements, namely hydraulic machines, hydraulic units, and hydraulic devices, a definitive criterion for assessing their technical level is synthesized. There were two stages in the study: theoretical and experimental. Initially, the most important factors influencing the reliability

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and efficiency of hydraulic devices were defined on the basis of operations research methods (hierarchy analysis method and multicriteria optimization). After the synthesis of the criterion, an experimental test was carried out based on a comparison of maintenance costs of real hydraulic devices. The obtained criterion allows one to make an assessment depending on constructive and operational indicators, based on common methodological principles. A comparison of the characteristics of maintenance costs of hydraulic devices per unit of power was made. Characteristic curves are hyperbolic, which proves the validity of the criterion.

Keywords: *Technical level; Criterion; Hydraulic machine; Hydraulic device; Energy efficiency*

Introduction

The creation of fundamentally new machines and equipment, improvement of existing ones using resource and energy-saving technologies are topical scientific and technical tasks [1]–[4]. The most complete requirements for resource savings are met by machines and process equipment with a hydraulic drive [5], which due to its known advantages has been widely used in various branches of mechanical engineering as actuating mechanisms of modern mechatronic modules [6], production process control systems technological and mobile machinery [7]–[9]. At the same time, the level of use of hydraulic drives and devices in machines is an indirect indicator of their technical level. When designing new machines and equipment, it is necessary to take into account the parameters of the hydraulic drive to be guided by. The solution of this issue is on a plane of establishing the technical level of its components, namely hydraulic machines, hydraulic units, and hydraulic devices, on the basis of comparison of their indicators with the indicators of the world's leading manufacturers of such equipment [10].

Considering only one element of the hydraulic drive pumps one can come to a conclusion that there are more than twenty of their varieties [11]. First of all, engineers consider the main indicators of the technical level: pressure, flow rate, and efficiency [12]. However, the great variety of other indicators complicates the selection process. In addition, for turbomachines, the coverage charts almost do not overlap, which allows one to select a particular pump in a rather unobtrusive way according to its characteristics and compare it with the pumps of other manufacturers (Figure 1) [13]–[15]. For positive displacement pumps, the task is more complicated, as illustrated in Figure 2. The main problem of selection is that pumps of various types and manufacturers have almost the same coverage charts [16, 17]. Also, proper pump selection is complicated by the possible use of jet pumps with low pressure, but high reliability and service life [18, 19].

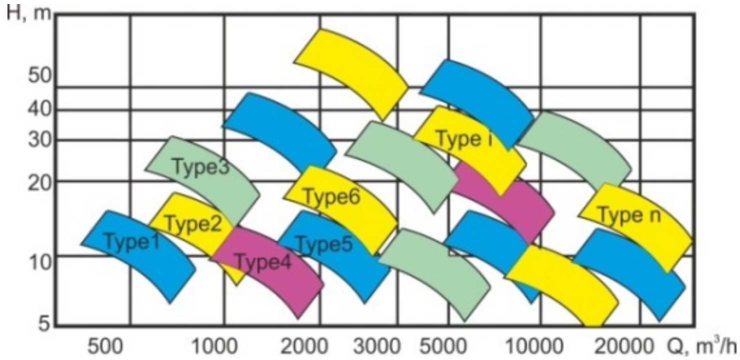


Figure 1: Coverage charts of turbomachines.

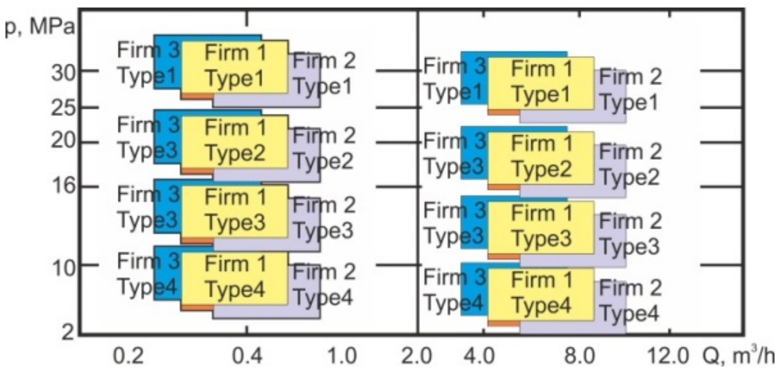


Figure 2: Coverage charts of positive displacement pumps.

A similar situation is observed for other elements of hydraulic drives: motors and hydraulic units. In addition, it is necessary to take into consideration many technical parameters that have an impact on the overall performance and life cycle [20, 21]. It leads to the generation of a variety of different parameters, factors, and coefficients that help researchers to make choices [22]–[24]. A large number of criteria for selecting hydraulic devices leads to significant errors during the selection process and to the fact that the final product, a hydraulic drive, does not meet the basic condition – economic viability.

When so many alternatives exist, it is possible to use the hierarchy analysis method [25, 26]. But it is known that this method is subjective, cumbersome, and requires the determination of weight coefficients, which does not allow one to compare clearly the technical level of pumps of various manufacturers (Figure 3).

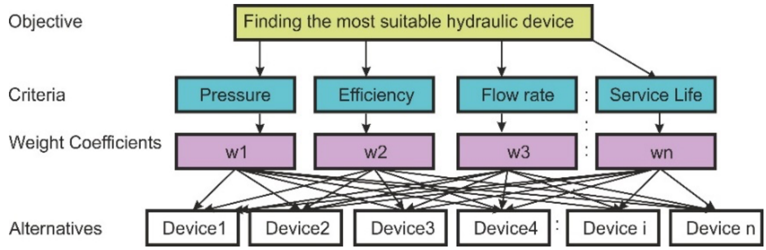


Figure 3: Hierarchical structural model for choosing hydraulic devices.

The main objective of the present study is to develop a detailed methodology towards the formulation of definitive assessment criteria of the technical level of hydraulic machines, hydraulic units, and devices. To achieve this objective, the following tasks are to be solved: to set problems and calculate the quality criteria for output characteristics of hydraulic machines, hydraulic units, and devices; to do a numerical study of the definitive assessment criterion of the technical level of hydraulic machines, hydraulic units, and devices; to discuss the obtained results and draw conclusions.

Progress in assessment criterion of technical level

In the scientific and technical literature, sufficient attention is given to the definition of the assessment criterion of the technical level of the individual elements of the hydraulic drive, but most of them relate to positive displacement hydraulic machines. The assessment of their technical level is carried out on the following indicators [27]:

Mass, which refers to the unit of the hydraulic motor torque (specific torque indicator):

$$k_T = \frac{m}{T} \tag{1}$$

where m is the hydraulic motor mass; T is the torque.

Mass, which refers to the unit of the power in the outlet of the hydraulic motor (specific power indicator):

$$k_P = \frac{m}{P_{M(P)}} \tag{2}$$

where $P_M(P_P)$ is the theoretical power of the motor or pump. Indices: M – hydraulic motor; P – hydraulic pump; ha – hydraulic drive or activator; n – hydraulic unit; hm – hydraulic device.

Mass, which refers to the unit of the volume that the hydraulic machine occupies (compactness factor):

$$k_T = \frac{m}{W} \tag{3}$$

where W is the volume that the hydraulic machine occupies. Note that material content is an indirect indicator of the economic efficiency of a product.

Power by a unit of the volume, which occupies a hydraulic motor (coefficient of power intensity):

$$k_{P/W} = \frac{P_M}{W} \tag{4}$$

Speed indicator:

$$C_V = n\sqrt[3]{q} \tag{5}$$

Power coefficient:

$$C_P = \Delta p n\sqrt[3]{q} \tag{6}$$

where n is the rotating speed; p is the pressure at the device outlet; q is the displacement.

It should be noted that each of the above criteria separately does not adequately characterize the technical level of the hydraulic machines. Therefore, one should compare the machines according to several criteria or select the main one, which reflects the greatest extent of the requirements imposed on a particular machine. It should be noted that these indicators of the technical level of hydraulic machines must be considered together with their efficiency.

Andrenko et al. [28] show a rise in the technical level of the hydraulic unit of the machine for coil winding of electric motors. Improvement is achieved by setting the optimal values of the tensile load of the wire and the rotating speed of the hydraulic motor shaft. The above methodology cannot be used to determine the technical level of hydraulic units, as it requires experimental research.

Kreinin et al. [29] consider factors influencing the selection of hydraulic drives decoupling, but in fact, the criterion was not given and it is proposed to consider all factors in aggregate. The application of the analytic hierarchy process when selecting layout schemes for a geokhod pumping station was reviewed in the study [30]. A fairly large number of investigators applied the method of analyzing hierarchies [26, 30, 31]. However, the hierarchical selection procedure is rather complicated, cumbersome, and dependent on subjective assessments.

In order to quantify the energy efficiency of an electrohydraulic drive with throttle control, the following criterion uses:

$$I_1 = \frac{1}{\tau}\int_0^{\tau}\frac{Q}{Q_t}dt \tag{7}$$

where τ is the operating time of the device; Q is the volume flow rate; Q_t is the theoretical volume flow rate through the hydraulic driver.

To find the optimal value of the criterion (Equation 1), it should be considered together with the criterion of the rotation uniformity, on the basis of which the goal function is determined, the form of which is not known in advance. This problem is solved by the method of conditional optimization. The criterion (Equation 7) does not fully take into account the power of the drive, as generally, the power of the hydraulic drive is a product of the pressure loss. In addition, it is impossible to compare drives of different types by the energy efficiency criterion, as their operating time T can vary significantly [32, 33]. It does not allow one to determine the technical level of the drive and to compare drives of a different type.

A relative integral estimate is often used for assessing the transient processes quality of hydraulic units:

$$J_Q = \frac{\int_0^{t_p}|y_1(t)-y_2(t)|dt}{\int_0^{t_p}y_1(t)dt}\cdot 100\% \tag{8}$$

where $y_1(t)$ is the set point of the reference quantity; $y_2(t)$ is the real value of the reference quantity; t_p is the time of the transient process.

Estimation (Equation 8) defines the ratio of the inequality of the area under the curves $y_1(t)$ and $y_2(t)$ to the area under the curve $y_1(t)$ for the time of the transient process t_p. The estimation allows comparing hydraulic units by a single criterion. Note that similarly to (Equation 8) one can take expressions for other variables. However, the relative integral estimate (Equation 8) does not allow one to do a comprehensive assessment of the characteristics of the hydraulic unit and to determine its technical level.

In world practice, the technical level of pumping equipment is determined by its energy efficiency. According to [34, 35], the energy efficiency index EEI (Energy Efficiency Index) is determined by the expression:

$$EEI = \frac{P_{L,avg}}{P_{ref}}C_{20\%} \tag{9}$$

where $P_{L,avg}$ is the average power consumed by the pump with the standardized loading profile. It is calculated according to expression (Equation 10) as the average power value consumed by the pump during its periods of operation:

$$P_{L,avg} = 0.06P_{L,100\%} + 0.15P_{L,75\%} + 0.35P_{L,50\%} + 0.44P_{L,25\%} \tag{10}$$

where P_{ref} is the reference power, design value for a circulating pump, defined for its specific type; $C_{20\%}$ is the legislative correction factor, which determines that only 20% of existing circulation pumps meet the requirements of EEI 0.20, $C_{20\%} = 0.49$.

The above energy efficiency index (Equation 9) is the integral efficiency of the pump, defined for its range of operation at nominal and non-nominal modes close to it, and only partially characterizes its technical level.

Standards [36, 37] show the energy efficiency determination method of five types of water pumps with power up to 150 kW. Standard [36] defines the evaluation procedure of the pump technical level at three points of the efficiency characteristic: Q_{PL} is the volume flow rate at the part load, $Q_{PL} = 0.75Q_{BEP}$; Q_{BEP} is the volume flow rate at the best efficiency point; Q_{OL} is the volume flow rate at the overload, $Q_{OL} = 1.1Q_{BEP}$. The minimum permissible efficiency is determined by the dependence, which includes the pump volume flow rate at the best efficiency point and the specific speed. In addition, the correction factor C, which takes into account the technical level of pumping equipment manufactured by European companies, is reduced to the value of the required minimum efficiency value. This coefficient depends on the type of pump, the rotating speed, and the index MEI. MEI is the minimum efficiency index, which reflects the share of low-tech products available on the market, which is subject to phasing out of sales.

To determine the correction factor C, prior knowledge of the equipment level is required. This coefficient depends on the pump type. It is impossible to determine it for the pump being designed. Thus, this approach cannot be effectively applied to determine the technical level of pumping equipment.

Andrenko et al. [38] determine the rational values of the labyrinth screw pumps parameters by their specific parameters, which cannot be used to determine their technical level. In order to evaluate the constructive and operational parameters of the hydraulic motors in [27], it is proposed to use a dimensionless efficiency criterion:

$$K = \frac{Tn_M\tau_S}{gmL} = 367.35\frac{Tn_M\tau_S}{mL} \quad (11)$$

where τ_S is the service life of the device; g is the gravitational acceleration; L is the characteristic dimension of the device:

$$L = \sqrt{D_M L_M} \quad (12)$$

D is the diameter of the device.

However, criterion (Equation 11) does not consider such important indicators of the hydraulic motor technical level as total efficiency, power factor, noise level caused by the operation of the hydraulic motor, vibration resistance, excessive overload (strength of the hydraulic motor parts). Such parameters are considered in [39]–[44]. The assessment criterion of the technical level of hydraulic units is calculated by comparing the aggregate of the quality indices of hydraulic devices being designed with the corresponding aggregate of indicators of the analog. An important indicator that determines the feasibility of production and their introduction into the industry is the economic effect, carried out by known methods. In this approach, a consolidated index of the technical level indicator is calculated for the technical level of the hydraulic machine, hydraulic unit, or device. It includes the weight of the parameter i, the definition of which encounters certain difficulties and significantly affects the values of this indicator. In addition, the results obtained greatly depend upon the selection accuracy of analog and standard. Thus, the above approach needs to be clarified.

Often the integral index of the hydraulic machine technical level, which is invariant to the level of the quality model, is determined by solving the nonhomogeneous linear equations system:

$$\begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} & q_{15} & -1 \\ 0 & q_{2\cdot 2} & q_{23} & q_{24} & q_{25} & -1 \\ 0 & 0 & q_{33} & q_{34} & q_{35} & -1 \\ 0 & 0 & 0 & q_{44} & q_{45} & -1 \\ 0 & 0 & 0 & 0 & q_{55} & -1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ U \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{13}$$

where U is the integral index of construction's technical level; q_{ij} is the normalized values of the single indices; $\lambda = (\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5)$ is the column of unknown weight coefficients that do not depend on the subject of expert examination and is determined by solving the system of equations.

This versatile model does not require the use of subjective expert methods. At each of its levels, one can consider the new properties that are inherent to the system as a whole. It is also possible to implement the analysis of analogs and the selection of options by a single comprehensive criterion of the technical level. Equation 13 can be written as follows equation:

$$K = 60\frac{Tn\tau}{gmLf_M} \tag{14}$$

However, in this study, interrelated parameters such as the probability of failure-free operation and failure to work are used as a reliability indicator. They are associated with medium resources and longevity and therefore are correlated. In addition, the developed single vibrational stability criteria are given only for positive displacement hydraulic machines, the value of the scale dimensional coefficient f_M included in (Equation 14) is not determined, there is no criterion that takes into account the noise level. The noise level is now one of the main criteria in the manufacturers' competition of hydraulics components, primarily pumps [45]. Moreover, the main parameters that determine the noise of pumps are their rotating speed and pressure. So, with a decrease in the rotating speed from 30 s^{-1} to 3.3 s^{-1}, the noise level is reduced by 15.20 dBA. The solution of the system of inhomogeneous linear equations (Equation 14), due to the uncertainty of their kind, in some cases, encounters great difficulty. The criterion (Equation 14) does not contain a precision indicator K_{prec} that characterizes the proximity to zero of the error of reproduction of the control signal.

In addition, (Equation 14) does not consider the inequality, which is determined by the dependence:

$$\delta = \frac{y_{max} - y_{min}}{y_{avg}} \tag{15}$$

where y_{max} is the maximum output value; y_{min} is the minimum output value; y_{avg} is the average output value.

This factor is important especially for hydraulic machines. In general, we have not found a comprehensive assessment criterion of technical level for components of the hydraulic drive – hydraulic devices which are based on unified methodological bases. The development of such a criterion that takes into account the maximum number of indicators is based on common methodological principles. Thus, the development of this criterion is an actual scientific and technical task.

Definitive assessment criterion of technical level

The proposed definitive assessment criterion of technical level for hydraulic devices is as follows:

$$K = \frac{L \cdot K_{P/W} \cdot \eta \cdot \tilde{P}(t) \cdot k_{ext} \cdot \delta \cdot K_{prec} \cdot K_{np}}{g \cdot C_V \cdot L_H \cdot k_W \cdot D_f \cdot \bar{L}_{mdBA}} \tag{16}$$

$$L = \begin{cases} \sqrt[3]{q} \ \ for\ the\ hydraulic\ pump\ and\ motor \\ D_n \ \ for\ the\ hydraulic\ units \\ \sqrt{A_{ha}} \end{cases} \tag{17}$$

where D_n is the diameter of the nominal bore; A_{ha} is the area of the blind side of the hydraulic actuator or its effective area; $K_{P/W}$ is the coefficient of the power intensity determined by (Equation 4). In the (Equation 4) P is the output power of the hydraulic motor or hydraulic device; η is the efficiency of the hydraulic device or its energy efficiency index EEI which determined by (Equation 9); $\tilde{P}(t)$ is the probability of non-failure operation of the hydraulic device; k_{ext} is the criterion of excessive overload:

$$k_{ext} = \frac{p_{max}}{[n_\sigma] p_{nom}} \tag{18}$$

where p_{max} is the maximum pressure in the device; p_{nom} is the nominal pressure in the device; $[n_\sigma]$ is the safety factor; C_V is the speed indicator.

$$C_V = \begin{cases} n\sqrt[3]{q} & for\ hydraulic\ machines \\ \frac{l_{ha}}{t_{ha}} & for\ hydraulic\ devices \end{cases} \tag{19}$$

where l_{ha} is the length of the displacement of the hydraulic actuator or the locking and regulating element of the hydraulic unit; t_{ha} is the piston rod movement time or movement time of the locking and regulating element of the hydraulic unit.

L_H is the characteristic size of the hydraulic device [27]. $L_H = \sqrt{D_{hM} L_{hM}}$, k_W is the coefficient of compactness (Equation 4); D_f is the quality factor of the hydraulic device that characterizes its vibrational stability:

$$D_f = \frac{2\pi \cdot f_0 \cdot E}{P_{pos}} \tag{20}$$

where f_0 is the resonant frequency of the hydraulic device; E is the energy stored by the oscillating system; P_{pos} is the dissipating power of the oscillating system; $\overline{L}_{mdBA}$ is the relative noise level of the hydraulic device. $\overline{L}_{mdBA} = L_{mdBA}/L_{m0\ dBA}$, where L_{mdBA} is the noise level when a hydraulic device is running; $L_{m0\ dBA}$ is the basic noise level in the design engineering bureau [45]; δ is the irregularity (Equation 15).

The proposed criterion allows evaluating the technical level of hydraulic devices, depending on their design and operational parameters. It can be done at the CAD (Computer-aided design) stage [46]–[49]. This criterion is based on common methodological principles based on the data given in the relevant directories or technical specifications for the design of the product.

The greater value of the definitive criterion, the higher the technical level of the hydraulic device, the higher energy efficiency, and other indicators. The designed hydraulic system will have the best efficiency and reliability. Note that if any coefficient included in the formula (Equation (16)) cannot be determined, then a unit is substituted for it. In this case, the coefficient of dimension is set before the definitive criterion. If any coefficient included in Equation 16 cannot be determined then this one is excluded from consideration for all other hydraulic devices, even if the necessary information has been found.

Calculated investigation

For calculations, we used the data of pumps, hydraulic motors, and directional valves given in the study [50]. We wrote down them in the corresponding tables and calculated the complex universal definitive criterion of the technical level according to (Equation 16). It has been established that the highest technical level of the examined pumps (Table 1) has an axial piston pump. It can be explained by its high power compared to other types of pumps.

Table 1: Technical characteristics and the definitive assessment criterion of the technical level of pumps

Pumps technical data, dimension	Pumps			
	Axial piston pump, 310	Pump RKP Moog	Gear pump, G11-24A	Rotary vane pump, NPL 40/6,3
Displacement q [sm^3]	28	45	40	40
Working pressure [MPa]	20	28	2.5	6.3
Rotating speed [1/min]	1920	2000	1450	960
Power [kW]	28	3.5	40	50
Nominal volume flow rate [l/min]	54	22	40	50
Efficiency	0.91	0.9	0.72	0.85
l [m·10^{-2}]	14.0	26.7	18.0	19.7
a [m·10^{-2}]	10.0	12.5	9.3	15.0
Mass [kg]	9	33	12	9.7
Service life [h]	-	-	-	4000
Average sound level [dBA]	-	64	-	74
$K_{P/W}/k_w$ [W/kg]	3111	106	250	443
C_V [m/s]	3498	4268	2975	1970
K	97.6	2.08	8.58	9.4

The results of the technical level calculation of the hydraulic motors (Table 2) show that the highest technical level has a gerotor hydraulic motor. It also indicates the legitimacy of the developed criterion application for the technical level assessment of hydraulic devices. The highest technical level is shown by Atos directional valves (Table 3). It can be explained by a higher nominal flow rate at the same diameter of the conventional passage and practically the same nominal pressure. In addition, the following example will show how easy to use the criterion in practice.

Comparison of hydraulic devices using criterion

To substantiate the criterion applicability, a comparison of the economic costs is made. The financial costs of the service:

$$\Phi = \Phi_s + \Phi_{sp} + \Phi_{nonc} \tag{22}$$

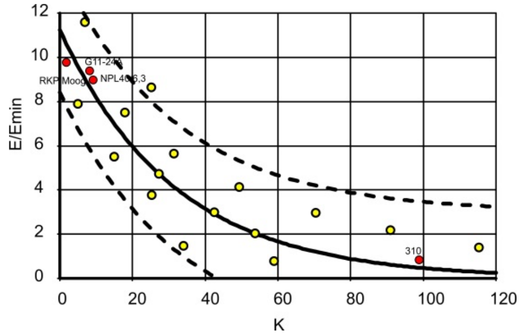
where Φ_s is the maintenance costs associated with shutting down production equipment and determined by the reliability of the devices; Φ_{sp} is the costs of spare parts for hydraulic machines and apparatus; Φ_{nonc} is the cost of the loss of financial resources associated with the fact that the hydraulic equipment was not used in optimal conditions for pressure and volume flow rate, which reduces the efficiency of the hydraulic drive.

Figure 4 shows the comparative characteristics of the costs of servicing hydraulic devices per unit of power (E). Indicators are given in the relative form. All parameters are divided by the minimum indicator in each group of hydraulic devices.

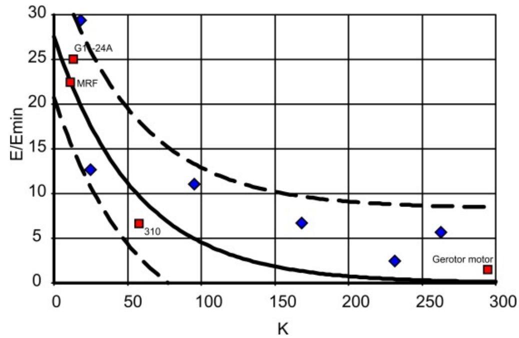
Table 2: Technical characteristics and the definitive assessment criterion of technical level for hydraulic motors

Motors technical data, dimension	Motors			
	Axial pistons motor, 310	Radial pistons motor, MRF	Gear motor, G11-24A	Gerotor motor
Displacement · q [sm^3]	28	160	14	100
Working pressure [MPa]	20	25	23	21
Torque [Nm]	84	597	2.83	250
Rotating speed [1/min]	1920	480	3500	160
Power [kW]	16.7	29.4	9.9	25
Efficiency	0.91	0.9	0.84	0.78
l [m·10^{-2}]	19.2	23.8	18.0	19.7
a [m·10^{-2}]	12.7	26.5	11.4	10.4
Mass [kg]	9	33.3	11.0	16.5
Service life [h]	-	-	-	4000
$K_{P/W}/k_W$ [W/kg]	1855	170	900	1515
C_V [m/s]	3498	720	5061	446
K	60.5	19.7	19.1	290

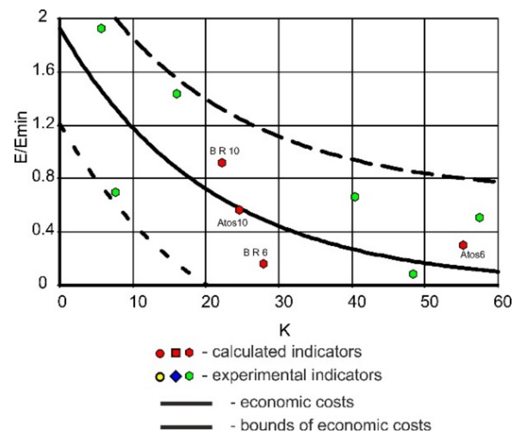
The experimental cost values are taken from the literature and operating experience of hydraulic equipment. Analyzing Figure 4, we can conclude that all the dependencies are hyperbolic in nature, which proves the validity of the application of the criterion obtained in the study. In addition, the dashed lines in the figure show the lines that bound all the experimental points. The nature of the dashed lines is also hyperbolic.



(a)



(b)



(c)

Figure 4: Economic costs of the operation of hydraulic devices depending on the complex K: a) pumps; b) hydraulic motors; c) hydraulic directional valves.

Table 3: Technical characteristics and the definitive assessment criterion of technical level for hydraulic directional valves

Directional valves technical data, dimension	Bosh Rexroth		Atos	
Control valve diameter D_n [m·10^{-3}]	6	10	6	10
Working pressure [MPa]	31,5	31,5	35	31,5
Nominal volume flow rate [l/min]	60	120	80	120
Power consumption [W]	8	35	30	39
Efficiency	0,94	0,94	0,93	0,95
Response time t_{ha} [s]	25	45	50	60
l [m·10^{-2}]	20,6	29,7	22,9	30,6
a [m·10^{-2}]	6,0	8,0	6,0	8,0
Sleeve valve travel l_{ha} [mm]	2	2	2	2
Mass [kg]	1,95	6	2	5
$K_{P/W}/k_w$ [W/kg]	4,103	5,833	15	7,8
C_V [m/s]	4,103	5,833	15	7,8
K	29,1	23,9	55,6	24,6

When a new hydraulic device is developed, it is impossible to determine the parameters of a technical level for it. In this case, methods of numerical solution of hydrodynamics (CFD - Computational fluid dynamics) come to the rescue [51, 52]. Using numerical simulation, you can predict the parameters of the device [53]–[56].

Conclusions

For the first time, the definitive assessment criterion of the technical level of hydraulic machines, hydraulic units, and devices is proposed. It allows assessing hydraulic devices depending on constructive and operational parameters based on unified methodological principles. The criterion is synthesized on the basis of the system analysis of the technical level estimated indicators of a wide range of the hydraulic drives element systems. The proposed criterion does not require the use of subjective expert evaluations and is obtained in the form of a simple algebraic expression that allows to determine the technical level of hydraulic devices according to catalogs or specifications and to assess their energy efficiency at the design stage. The efficiency of using the developed criterion is proved. An example of calculating the proposed criterion for a specific hydraulic device is given. Using the proposed criterion, the best hydraulic devices are determined.

After the synthesis of the criterion, an experimental test based on a comparison of maintenance costs of hydraulic devices was carried out. Maintenance costs consisted of maintenance service costs, spare part costs, and power losses due to the use of hydraulic devices in non-optimal duties. The comparison of cost characteristics is carried out in accordance with the power of the devices, i.e. all costs are attributed to the minimum power in each group $E_{min} = \Phi/P$. Characteristic curves are hyperbolic, which proves the validity of the criterion. Devices with better technical indicators have higher indicators of the developed criterion.

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Appendix

This example illustrates the use of definitive assessment criterion.
The rotary vane pump NPL 40/6,3 has parameters that indicated in Table 1 ($q = 40$ sm^3, $p = 6.3$ MPa, $n = 960$ 1/min, $P = 4.3$ kW, $Q = 50$ l/min, $\eta =$ $= 0.85$, $l = 19.7 \cdot 10^{-2}$ m, $a = 15 \cdot 10^{-2}$ m, $m = 9.7$ kg, $\tau_S = 4000$ h, $L_{mdBA} = 74$ dBA).

Solution

The proposed definitive assessment criterion of technical level of hydraulic machines:

$$K = \frac{L \cdot K_{P/W} \cdot \eta \cdot \tilde{P}(t) \cdot k_{ext} \cdot \delta \cdot K_{prec} \cdot K_{np}}{g \cdot C_V \cdot L_H \cdot k_W \cdot D_f \cdot \bar{L}_{mdBA}}$$

Power by unit of the volume, which occupies a hydraulic motor (coefficient of power intensity):

$$K_{P/W} = \frac{P_M}{W} = \frac{4300}{(15 \cdot 10^{-2})^2 \cdot 19.7 \cdot 10^{-2}} = 0.97 \cdot 10^6 \text{ W/m}^3$$

The probability of no-failure operation of the hydraulic device is:

$$\tilde{P}(t) = e^{-1000/\tau_s} = e^{-1000/4000} = 0.779$$

Since the coefficients k_{ext}, δ, K_{prec}, K_{np} could not be determined, we substitute them into the final formula with the values 1.

The speed indicator is:

$$C_V = n\sqrt[3]{q} = 60 \cdot 960 \cdot \sqrt[3]{40 \cdot 10^{-6}} = 1970 \text{ m/s}.$$

The characteristic size of the pump:

$$L_H = \sqrt{D_{hM} L_{hM}} = \sqrt{15 \cdot 10^{-2} \cdot 0.197} = 0.172 \text{ m}$$

The coefficient of compactness:

$$k_W = \frac{m}{W} = \frac{m}{a^2 l} = \frac{9.7}{(15 \cdot 10^{-2})^2 \cdot 0.197} = 2190 \text{ kg/m}^3$$

The relative noise level of the hydraulic device:

$$\bar{L}_{mdBA} = \frac{L_{mdBA}}{L_{m0\ dBA}} = \frac{74}{40} = 1.85$$

The proposed definitive assessment criterion of technical level for hydraulic machines $K = 9.4$.