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The identification of parameters of the electrohydraulic complex with cavitation oscillations based on a mathematical model

***Abstract**. It is demonstrated that the functioning of electrohydraulic complexes in unsteady modes of operation is accompanied by the deviation of the main parameters of the pumping and pipeline equipment from the rated values. The expediency of using the energy method based on the energy balance equations during the identification of the parameters of the electrohydraulic complex is substantiated. The systems of identification equations at different degrees of development of cavitation oscillations in the hydraulic network are obtained. Their solution makes it possible to calculate unknown parameters. It is shown that the total resistance of pumping and pipeline equipment is more affected by the development of cavitation oscillations.*

***Streszczenie.** Pokazano, że funkcjonowaniu zespołów elektrohydraulicznych w niestacjonarnych trybach pracy towarzyszy odchylenie głównych parametrów urządzeń pompowych i rurociągowych od wartości nominalnych. Uzasadniona jest celowość wykorzystania metody energetycznej opartej na równaniach bilansu energetycznego podczas identyfikacji parametrów zespołu elektrohydraulicznego. Uzyskano układy równań identyfikacyjnych przy różnych stopniach rozwoju oscylacji kawitacyjnych w sieci hydraulicznej, których rozwiązanie umożliwiło obliczenie nieznanych parametrów. Wykazano, że na całkowity opór czynny urządzeń pompujących i rurociągowych większy wpływ ma rozwój oscylacji kawitacyjnych. (**Identyfikacja parametrów zespołu elektrohydraulicznego z oscylacjami kawitacyjnymi na podstawie modelu matematycznego**)*

Keywords: electrohydraulic complex, energy balance equation, energy method, identification of parameters.
Słowa kluczowe: kompleks elektrohydrauliczny, równanie bilansu energetycznego, metoda energetyczna, identyfikacja parametrów.

Introduction

During the adjustment of the technological parameters of electrohydraulic complexes (EHC), switching on/off of the pumping unit (PU) or individual sections of the pipeline network, the operation of the shut-off and regulating valves, changes in the thermodynamic properties of the transported liquid, there arise modes that lead to the development of unsteady hydrodynamic processes: pressure pulsations, hydraulic shocks, cavitation phenomena, surge, etc. [1], [2]. The EHC operation in unsteady modes is accompanied by the development of wave phenomena. It results in time variation of the EHC current parameters: head, discharge and hydraulic power, deviation of parameters of pumping and pipeline equipment from the rated values, shift of the operating mode point and reduction of PU efficiency [3].

To ensure energy-efficient operation modes of the electromechanical system (EMS) of the EHC, it is necessary to identify the current parameters (hydraulic resistance, inductive reactance and capacitance, power losses, efficiency) of pumping and pipeline equipment in both steady and unsteady modes of operation [2], [3].

Existing methods for determining parameters (pressure, discharge, efficiency, active power, hydraulic resistance of the pump and pipeline) are characterized by low measurement accuracy caused by the use of empirical dependences; the possibility of determining the parameters of only individual EHC elements; the need to withdraw the electrohydraulic equipment for parameter identification [4]. Such approaches consider the hydrodynamic network only from the standpoint of hydrodynamics, and not as an element of the power channel of the electromechanical system of the EHC, the change in whose parameters affects the energy processes in the entire hydrotransport system. Taking into account the above, it is appropriate to use the energy method based on power balance equations when determining the parameters of the hydraulic system. This method is used in the task of building diagnostic systems and identifying parameters of electric motors [5], taking into account acquired defects or damage without the need to remove the equipment from the production process, compensation of higher harmonic components of the power supply voltage [6]. Therefore, the development of the energy method based on the harmonic analysis of instantaneous power in the tasks of identifying the parameters of electrohydraulic complexes of various purposes and complexity of the technological scheme deserves attention.

It should be noted that recently, automatic control systems of EHC based on adjustable asynchronous electric drive of pumping units have been actively implemented, which take into account the change in operational characteristics during the aging of electromechanical equipment [7], the state of the main structural nodes [8], controllability in emergency modes of operation [9].

The purpose of the paper is to identify the parameters of the electrohydraulic complex with an adjustable electric driveduring during the development of cavitation oscillations in the pipeline network using the energy method based on a mathematical model.

The method and results of the research

The analysis of energy conversion processes in EHC is based on the equations of the power balance between the power source $p_s(t)$ and the power $p_i(t)$ on the elements of the equivalent electrical circuit: $p_s(t)=\sum_{i=1}^{I} p_i(t)$, where i – the index of the corresponding EHC element [9] – [11].

So, for the simplest EHC, which includes a variable-frequency PU, a hydraulic network and a consumer, the power loss distribution scheme includes a source of hydraulic power (pump):

(1) $$p_s = \rho g H_0 \nu^2 Q_p;$$

power losses on the resistance of the pump

(2) $$\Delta p_p = \rho g R_p Q_p^3;$$

power losses on the resistance of the pipeline network

(3) $$\Delta p_{R\,net} = \rho g R_{net} Q_{net}^3;$$

power losses on the inductive reactance of the pipeline network

(4) $$\Delta p_{L\,net} = \rho g L_{net} \frac{dQ_{net}}{dt} Q_{net};$$

loss of hydraulic power to overcome back pressure in the hydraulic network

(5) $$\Delta p_{st} = \rho g H_{st} Q_{con};$$

hydraulic power at the consumer

(6) $$p_{con} = \rho g R_{con} Q_{con}^3.$$

In expressions (1)–(6) the following notations are introduced: $H_0 \nu^2$ – hydraulic energy source; ν – relative frequency of rotation of the impeller of the pump; R_p, R_{net}, R_{com} – hydraulic resistance of the pump, pipeline and consumer, respectively; L_{net} – inductive reactance of the pipeline; H^{st} – source of static back pressure; ρ – density of the pumped medium; g – acceleration of gravity; Q_p, Q_{net}, Q_{con} – consumption at PU output, in the hydroelectric network and at the consumer, respectively.

Then the energy balance equation has the form [9]:

(7)
$$p_s(t) = \Delta p_p(t) + \Delta p_{Rnet}(t) + \Delta p_{Lnet}(t) + \Delta p_{st}(t) + p_{con}(t).$$

The harmonic analysis of the power components [12] included in equation (7) made it possible to obtain a system of identification equations in the form of energy balance equations for individual components of hydraulic power between the hydraulic power source and the EHC elements:

(8(
$$\left.\begin{aligned}
&P_{s0} = P_{st0} + P_{Rp0} + P_{Rnet\,0} + P_{Lnet\,0} + P_{Rcon0};\\
&P_{s1a} = P_{st1a} + P_{Rp1a} + P_{Rnet\,1a} + P_{Lnet1a} + P_{Rcon1a};\\
&P_{s1b} = P_{st1b} + P_{Rp1b} + P_{Rnet\,1b} + P_{Lnet\,1b} + P_{Rcon1b};\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&P_{s\,ka} = P_{stka} + P_{Rp\,ka} + P_{Rnet\,ka} + P_{Lnet\,ka} + P_{Rcon\,ka};\\
&P_{s\,kb} = P_{st\,kb} + P_{Rp\,kb} + P_{Rnet\,kb} + P_{Lnet\,kb} + P_{Rcon\,kb}
\end{aligned}\right\}$$

where constant power components correspond to index "0"; cosine and sine components correspond to indices "a", "b", respectively; P_{Rp}, P_{Rnet}, P_{Lnet} – the amplitude values of hydraulic power losses at the hydraulic resistance of the pump, at the resistance and inductive reactance of the hydraulic network, respectively; P_{con} – the amplitude value of hydraulic power at the consumer; k – power signal harmonic number.

For the simplest EHC, when finding five unknown parameters (hydraulic resistances of the pump R_p, section of the pipeline network R_{net} and the consumer R_{con}, inductive reactance of the hydraulic network L_{net} and the amount of back pressure H_{st}), it is sufficient to use the first five equations that reflect the picture of the energy balance between the most important harmonic components of hydraulic power.

The representation of the system of linear equations (8) in matrix form:

(9) $$AX = B$$

where $$A = \begin{vmatrix} P_{st0} & P_{Rp0} & P_{Rnet0} & P_{Rcon0} \\ P_{st1a} & P_{Rp1a} & P_{Rnet1a} & P_{Rcon1a} \\ P_{st1b} & Rp1b & P_{Rnet1b} & P_{Rcon1b} \\ P_{st2a} & P_{Rp2a} & P_{Rnet2a} & P_{Rcon2a} \end{vmatrix}; \qquad B = \begin{vmatrix} P_{s0} \\ P_{s1a} \\ P_{s1b} \\ P_{s12} \end{vmatrix};$$

$X = \begin{vmatrix} H_{st} \\ R_p \\ R_{net} \\ R_{con} \end{vmatrix}$; and its solution by the matrix inversion method A^{-1} makes it possible to obtain the desired values of the EHC equivalent circuit.

One of the most negative consequences of unsteady processes consists in cavitation phenomena, caused by a local decrease in pressure in the liquid (below the pressure of saturated vapors) [13], [14]. it leads to periodic self-oscillations of pressure and productivity, erosive destruction of the material, changes in the parameters (efficiency, hydraulic resistance) of the hydraulic system.

When identifying the parameters of the hydraulic system, it is advisable to represent the EHC by an equivalent circuit based on the method of electro-hydraulic analogy (MEHA), in which the main electrical equations are transformed into the corresponding hydraulic relations [10], [11]. Thus, in order to take into account the nonlinear processes in the pipeline network, a cavitation block consisting of a nonlinear hydraulic resistance $R_{kav}(t)$ is introduced to the equivalent circuit (Fig. 1). It describes periodic cavitation oscillations in the pipeline network and is represented by a trigonometric series of the form:

(11) $$R_{kav}(t) = a_0 + \sum_{n=1}^{N} a_n \, sin(n\Omega_{kav} t)$$

where a_0, a_n – coefficients of the trigonometric series; $\Omega_{kav} = 2\pi f_{kav}$ – angular frequency of cavitation oscillations; $f_{kav} = 1/T_{kav}, T_{kav}$ – frequency and period of cavitation oscillations, respectively; $n,\ N$ – the number and quantity of harmonics of the hydraulic resistance signal of the cavitation channel, respectively. The condition for the activation of the key K is a decrease in the pressure in the pipeline below the pressure of saturated vapors, caused by a change in the operating mode of the consumer R_{con}.

The occurrence of cavitation processes in the pipeline leads to a periodic non-sinusoidal change in productivity at PU outlet [9]:

$$Q_p(t) = d(V_{kav}(t))/dt = Q_{p0} + \sum_{n=1}^{N} Q_{pn} \, cos(n\Omega_{kav} t)$$
(12)

where $V_{kav}(t) = k_{kav} R_{kav}(t)$ – a signal of a change in the volume of the cavitation cavern; k_{kav} – proportionality coefficient; Q_{p0}, Q_{pn} – the amplitude values of the constant and cosine n-th harmonic of the discharge signal, respectively.

Taking into account (12), the hydraulic power at the output of the hydraulic power source:

$$p_s(t) = \rho g H_0 \nu^2 Q_p(t) =$$
$$= \rho g H_0 \nu^2 \left(Q_0 + \sum_{l=1}^{L} Q_{la} \, cos(\Omega_l t) + \sum_{l=1}^{L} Q_{lb} \, sin(\Omega_l t) \right) =$$

(13) $$= \sum_{r=1}^{R} P_{rs0} + \sum_{r=1}^{R} P_{rsa} \, cos(\Omega_r t) + \sum_{r=1}^{R} P_{rsb} \, sin(\Omega_r t)$$

where r, R – the number and quantity of harmonics of the hydraulic power signal at the output of the hydraulic power source, respectively; $P_{rs\,0}, P_{rsa}, P_{rsb}$ – the amplitude values of the constant and orthogonal cosine and sine components of the hydraulic power signal of the hydraulic power source, respectively; Ω_r – the angular frequency of the hydraulic power signal of the pump.

The equation of EHC energy balance during the development of cavitation processes in the pipeline network has the form:

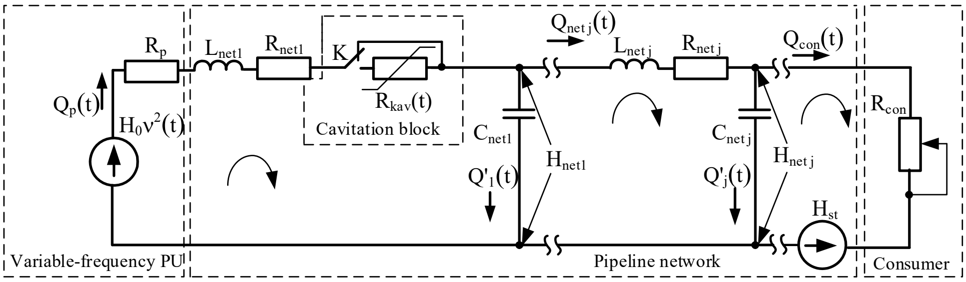


Fig. 1. EHC equivalent circuit taking into account the development of cavitation processes in the hydraulic network

$$p_s(t) = \Delta p_p(t) + \Delta p_{Rnet\ j}(t) + \Delta p_{Lnet\ j}(t) + \\ + \Delta p_{Cnet\ j}(t) + \Delta p_{st}(t) + p_{con}(t). \tag{14}$$

To determine the parameters of the EHC, a mathematical model of the variable-frequency electric drive of the pump is proposed, the description of the elements of which is given in [9], [10]. The frequency converter (FC) forms a quadratic control law and is described by an aperiodic link of the first order. The operation of an induction motor (IM) is described by the model equations in $u,\nu,0$-coordinates, where the differential equations are presented in the form of flux linkages for the synchronous coordinate system. The pump, represented by an aperiodic link, creates a quadratic moment of resistance on the motor shaft. The pipeline network with the *j*-th number of sections is described by the equations of pressure wave propagation in the pipeline, the solution of which by the finite element method allows representing the hydraulic network as separate sections with equal parameters. The cavitation formation block is represented by a separate circuit that can be connected to any section of the pipeline network.

Consider the case when signal $R_{kav}(t)$, and, accordingly, signal $Q_p(t)$, contains a constant and three harmonic components:

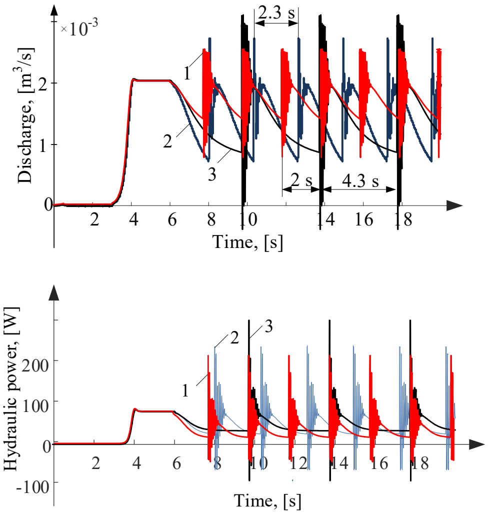
$$Q_p(t) = Q_{p0} + Q_{p1}\cos(\Omega_{kav}t) + \\ + Q_{p2}\cos(2\Omega_{kav}t) + Qp\cos(3\Omega_{kav}t). \tag{15}$$

The object of the research is a mathematical model of a EHC laboratory, a description of the electromechanical equipment and its functional capabilities are given in more detail in [9]. Technical parameters of the equipment: motor: P_n = 830 W, U_n = 380 V, ω_n = 303.7 s^{-1}, I_n = 1.7 A; pump: $Q_p = 0.00138$ m^3/s, H_p = 4.7 m and pipeline network: $d = 0.05$ m, $l = 12$ m.

Fig. 2 contains the curves of changes in discharge and hydraulic power at the outlet of the first section of the pipeline network to which the cavitation forming block is connected, during the development of cavitation of various degrees $n_{kav} = V_{cur}/V_0$, where V_0, V_{cur} – the initial and current values of the volume of the cavitation cavity, respectively. It is found that an increase in the degree of development of cavitation is accompanied by an increase in the amplitude and period of oscillations: at $n_{kav1} = 3.7$ theperiod is 2 s, at $n_{kav3} = 19.7$ – 2.3 s; at $n_{kav5} = 31$ – 4.3 s.

In this case, system (8) consists of 19 equations, the first three of which are used to find the unknown total hydraulic resistances $R_\Sigma = R_p + R_{net1} + R_{net2} + R_{con}$ of the pump, pipeline and consumer, inductive reactance L_Σ and capacitance C_Σ of the hydronetwork sections:

$$\left.\begin{aligned} P_{s\,0} &= P_{\Sigma 0} + P_{Lnet\Sigma 0} + P_{Cnet\Sigma 0}; \\ P_{s\,1a} &= P_{\Sigma 1a} + P_{Lnet\Sigma 1a} + P_{Cnet\Sigma 1a}; \\ P_{s\,1b} &= P_{\Sigma 1b} + P_{Lnet\Sigma 1b} + P_{Cnet\Sigma 1b}. \end{aligned}\right\} \tag{16}$$



a)

b)

Fig. 2. The curves of changes in discharge (a) and hydraulic power (b) at the output of the first section at n_{kav1} (1), n_{kav3} (2) and n_{kav5} (3)

The results of the calculation of EHC parameters based on model are summarized in Table 1 (column I). It is found that when cavitation oscillations occur with different degrees n_{kav} the total hydraulic resistance R_Σ increases in the pipeline network, which is caused by the growth of the volume of cavitation cavities in the liquid flow: at $n_{kav2} = 7$ resistance R_Σ grows by 1.03 times; at $n_{kav4} = 26$ and $n_{kav5} = 31.3$ – respectively by 2.05 and 2.63 times.

For comparison, the parameters of the laboratory physical EHC were calculated by the energy method using the signals obtained experimentally. The results of identification of parameters of physical EHC are shown in Table 1 (column II).

Thus, a comparative analysis of the parameters of the mathematical model calculated by the energy method (Fig. 3, dotted line) and the experimental EHC (Fig. 3, solid line) showed a sufficiently high convergence of the results: coefficient of determination R^2 lies within (0.9..0.98). The following designations are adopted in Fig. 3: $r = R_{\Sigma r}/R_{\Sigma i}$, $l = L_{\Sigma r}/L_{\Sigma i}$, $c = C_{\Sigma r}/C_{\Sigma i}$, $R_{\Sigma r}, R_{\Sigma i}$, $L_{\Sigma r}, L_{\Sigma i}$, $C_{\Sigma r}, C_{\Sigma i}$ – the values of hydraulic resistance, inductive reactance and capacitance in the system with cavitation and in its absence, respectively.

At the same time, the analysis of the curves of changes in EHC parameters depending on the degree of cavitation development (Fig. 3) revealed that the total active resistance of electrohydraulic equipment is more affected by cavitation oscillations. This is confirmed by the curve of changes in relative hydraulic resistance r depending on the degree n_{kav} of development of cavitation.

Table1. The results of the identification of EHC parameters

Cavitation degree, n_{kav}	Parameter of EHC equivalent circuit					
	R_{Σ} , kg/m^{4}s		$L_{net\Sigma}$, kg/m^4		$C_{net\Sigma}$, m^{-1}	
	I	II	I	II	I	II
System without cavitation	$1.86\cdot10^7$	$1.698\cdot10^7$	$1.041\cdot10^3$	$1.14\cdot10^3$	$1.3\cdot10^{-4}$	$1.429\cdot10^{-4}$
$n_{kav1} = 3.7$	$1.87\cdot10^7$	$1.7\cdot10^7$	$1.12\cdot10^3$	$1.244\cdot10^3$	$1.28\cdot10^{-4}$	$1.42\cdot10^{-4}$
$n_{kav2} = 7$	$1.918\cdot10^7$	$1.73\cdot10^7$	$1.172\cdot10^3$	$1.317\cdot10^3$	$1.32\cdot10^{-4}$	$1.45\cdot10^{-4}$
$n_{kav3} = 19.7$	$2.38\cdot10^7$	$2.21\cdot10^7$	$1.341\cdot10^3$	$1.474\cdot10^3$	$1.3\cdot10^{-4}$	$1.413\cdot10^{-4}$
$n_{kav4} = 26$	$3.817\cdot10^7$	$3.597\cdot10^7$	$1.361\cdot10^3$	$1.512\cdot10^3$	$1.28\cdot10^{-4}$	$1.376\cdot10^{-4}$
$n_{kav5} = 31.3$	$4.898\cdot10^7$	$4.585\cdot10^7$	$1.392\cdot10^3$	$1.547\cdot10^3$	$1.29\cdot10^{-4}$	$1.43\cdot10^{-4}$

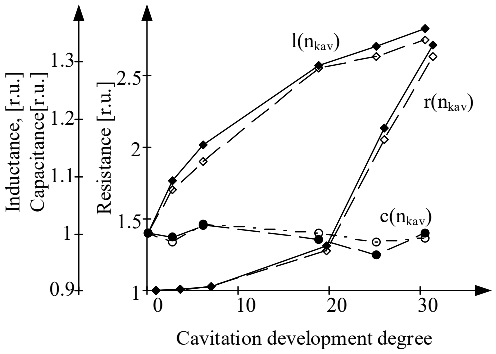


Fig.3 The dependence of changes in the relative values of EHC equivalent circuit parameters on the degree of development of cavitation n_{kav}

It is found that at small n_{kav} the change in the relative hydraulic resistance is insignificant; with developed cavitation there is a sharp increase in r .

Conclusions

The possibility of applying the energy method of identifying the parameters of the electrohydraulic complex based on the energy balance equations between the power source and the elements of the power channel has been proven. It has been demonstrated that the method is based on the formation of identification equations on the grounds of harmonic analysis of hydraulic power using equivalent circuits, which take into account the configuration of the pipeline and the occurrence of unsteady processes in the hydraulic system.

It has been shown that when cavitation oscillations occur in the pipeline network, the total active hydraulic resistance increases, which is caused by the growth of the volume of cavitation cavities in the liquid flow. At the same time, when the relative threshold value of the hydraulic resistance is reached, clogging of the pipeline is possible. This necessitates taking measures for cavitation protection of hydraulic equipment: opening of aeration valves to bleed air, changing pumping unit operating mode to exit the cavitation zone, etc.

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