STUDY OF THE CHARACTERISTICS OF THE RUNNER BLADE SYSTEM OF A HYDRAULIC MACHINE

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Abstract - The paper is devoted to the development of a methodology for determining and analyzing the main characteristics of the elementary lattices of the runner blade system of a reversible hydraulic machine. Equations that describe the kinematics of the flow in absolute and relative motion at the inlet and outlet of the runner are given. This method of calculation and analysis of elementary lattice characteristics makes it possible to evaluate their influence on the runner of a reversible hydraulic machine, which helps to assess the degree of consistency of elementary lattices that make up the runner spatial lattice. To study the operating process, the equations of dimensionless coefficients of head, moment, and power were applied to the runner's elementary lattice. The relationship between the hydrodynamic, kinematic, and energy parameters of elementary lattices and the spatial lattice of the runner is shown. The regularities of changes in the hydrodynamic characteristics of elementary lattices are determined, which makes it possible to determine the loss coefficient of the runner in the optimal operation mode and to evaluate the consistency of the runner elementary lattices with each other. Numerical modeling of a 3D model of the ORO200 runner was carried out, resulting in a spatial model of the fluid flow. The distribution of static pressure and velocity components is obtained. All these approaches help to obtain the nature of fluid flow in the blade system.

Keywords: Hybrid power systems, Renewable energy sources, Hydroelectric power generation, Fluid flow, Energy efficiency, Power engineering computing, Mathematical model, Numerical models.

1. Introduction

The current situation in Ukraine has led to serious changes in the balance of power that determine the impact on energy security in the world. An accelerated transition to renewable energy sources is one of the important accents of the REPpowerEU package, with which the European Commission responded to the aggravation of the global energy crisis. Ukraine can become a leader in the development of "green" energy in the future. With the expansion of energy cooperation between countries, it is planned – until 2030, to increase the capacity of "green" energy in Ukraine from 9 to 30 GW. The development of "green" energy, especially solar and wind power plants, creates risks of reliability imbalance of the energy system. Renewable energy sources are characterized by non-guaranteed changing data of electricity generation during the day, as well as significant seasonal fluctuations in production volumes. According to the conclusion of the World Hydropower Congress, held in 2021, to ensure further growth in the share of renewable energy, it is necessary to increase the volume of balancing and shunting power. Electric storage systems (including pumped storage power plants) contribute to the stable functioning of the energy system and allow the development of renewable energy facilities, reducing imbalances in the network caused by uneven loads from consumers [1-4]. From the analysis of works on the study of the working process of reversible hydraulic
machines, it follows that at present the issue of creating water passages of reversible hydraulic machines is quite relevant [5-8]. Also of interest are an investigation of new rotor blade designs conceived to produce higher exit relative kinetic energy of a mixed flow turbine [9-10]. When developing a reversible hydraulic machine water passage, involves carrying out numerous computational studies that are necessary to find the influence of geometric and mode parameters on the parameters of the optimal operation mode and energy characteristics. The basis for numerical analysis is mathematical models of the working process. Not only the development of working process modeling methods that use the results of solving problems of the three-dimensional flow viscous flow [8, 11] but also methods for calculating energy characteristics based on simplified flow models are widely used as well. Improving the energy parameters of a reversible hydraulic machine depends on the hydrodynamic characteristics of the parts of the water passage. In the study and analysis of the hydrodynamic characteristics of blade systems (wicket gate and runner), it is necessary to know both the averaged flow parameters and the distribution of the kinematic flow parameters in the characteristic sections of the water passage. The distribution of energy and kinematic characteristics along each elementary lattice that makes up the blade system of the runner of a reversible hydraulic machine is of interest also.

When modifying the runner of a reversible hydraulic machine, it becomes necessary to make changes to the geometry of individual lattices. Quantitative assessment of changes introduced into the water passage geometry should be based on the kinematic and energy analysis of individual runner lattices that make up the runner. An analysis of the formation of the energy and kinematic characteristics of the runner spatial lattice is necessary to identify the role (contribution) of a separate lattice (peripheral, bushing) while providing the required indicators. Therefore, the task of analyzing the force interaction of a flow with individual lattices should be considered very relevant.

2. Kinematic Characteristics of Elementary Lattices

The dependence of the output flow parameters on the input and mode parameters will be understood as the kinematic characteristics of elementary lattices.

In the considered case, the geometry of each of the elementary lattices that make up the runner remains unchanged. The meridional velocity at the input edge and output edge can be represented as: $C_{in} = B_1(l_1)Q$ and $C_{2m} = B_2(l_2)Q$. The parameters $B_1(l_1), B_2(l_2)$ depend on the lattice geometry on a given current surface and are independent of the mode; curvilinear coordinates $l_1$ and $l_2$ are measured from the bushing along the input and output edges of the runner blade, respectively.

Within the considered approximate flow model, the meridional velocity coefficient $C_m = \frac{Q}{Q}$ and at each point of the input and output edges remains constant (does not depend on the regime parameters $\omega$ and $Q$). The values of the meridional velocity coefficients are found from the flow rate equation:

$$C_{in} = B_1' = \frac{1}{n2\pi i|\Delta_i|}, \quad (1)$$
$$C_{2m} = B_2' = \frac{1}{n2\pi j|\Delta_j|}, \quad (2)$$

where $\Delta_i',\Delta_j'$ are the thicknesses of the flow layer of elementary lattices on the input and output edges, referred to the runner diameter to $D = 1$ m, $r_1' = r_1/D$ and $r_2' = r_2/D$.

The distribution of the meridional velocity coefficient $B_1'$ along the output edge is determined by the accepted meridional flow and is preserved with a mode change.

The flow angles in absolute and relative motion at the entrance to the elementary lattice are found in the kinematic equations [5, 6]:

$$ctg \alpha_i = \frac{1}{2\pi B_1' r_1'} \frac{\Gamma_i D}{Q}, \quad (3)$$
$$ctg \beta_i = \frac{r_1'}{B_1' k_0} - ctg \alpha_i, \quad (4)$$
$$ctg \beta_i = \frac{r_1'}{B_1' k_0} - \frac{1}{2\pi B_1' r_1'} \frac{\Gamma_i D}{Q}, \quad (5)$$
$$ctg \beta_i = \frac{r_1'}{B_1' k_0} - \frac{m}{2\pi B_1' r_1'} \frac{\bar{\Gamma}_i D}{Q}, \quad (6)$$

In the above formulas $k_0 = \omega D/\bar{Q} = \pi n_0/30 Q_0'$ is the generalized mode parameter; $\frac{\Gamma_0 D}{Q}$ is dimensionless kinematic complex behind the wicket gate; $\bar{\Gamma}_0 D$ is the average kinematic complex; $m = \left(\frac{\Gamma_0 D}{Q} / \bar{\Gamma}_0 D\right)$ is the coefficient taking into account the unevenness of the inlet circulation along the height of the blade.
\( \alpha \) is an angle of flow in absolute motion in the inlet section of the runner; \( \beta_1 \) is an angle of flow at the inlet to the runner in relative motion.

Circulation and flow angles in absolute and relative motion at the outlet of the elementary lattice:

\[
\Gamma_2 = k \Gamma_1 - (1-k)q \operatorname{ctg} \beta_{02} + (1-k)2\pi r_a^2 \omega, \tag{7}
\]

\[
\operatorname{ctg} \alpha_2 = k \frac{r_1^2}{r_2^2} B_2' \operatorname{ctg} \beta_1 - (1-k) \operatorname{ctg} \beta_{02} +
+ (1-k) \frac{r_2^3}{r_1^2} B_1' \frac{\omega D^3}{Q}, \tag{8}
\]

\[
\operatorname{ctg} \beta_2 = k \frac{r_1^2}{r_2^2} B_2' \operatorname{ctg} \beta_1 + (1-k) \operatorname{ctg} \beta_{02} - (1-k) \times
\times \left[ \frac{r_2^3}{r_1^2} - 1 - k \right] \frac{r_2^3}{r_1^2} B_1' \frac{\omega D^3}{Q}. \tag{9}
\]

In the formulas \( k, r_2 \) are the hydrodynamic parameters of the elementary lattice:

\[
q = \frac{\Delta Q}{\Delta_2} = 2\pi r_a C_{2m} \text{ is the flow rate related to the thickness of the flow layer near the output edge.}
\]

For thick runner lattices of a reversible hydraulic machine, the transparency coefficient \( k \) is small, therefore, we can assume \( k = 0 \). The active lattice radius is found using simplified flow models in the runner channels:

\[
r_a = r_2 \sqrt{1 + \frac{\pi}{z} \sin \beta_2 \sin \gamma_2}. \tag{10}
\]

To determine the angle of the shock-free flow direction behind the lattice \( \beta_{02} \), a correction is introduced that takes into account its difference from the outlet geometric angle \( \beta_{02} = \beta_{3r} + \Delta \beta_{02} \).

The above formulas solve the problem of calculating meridional velocities and flow angles (in absolute and relative motion) near the output edge. The circumferential speed component is found in the output velocity triangle \( C_{2r} = C_{2r} \operatorname{ctg} \alpha_2 \).

For each of the elementary lattices of the runner, the circulation relation equation is valid in the dimensionless form:

\[
\frac{\Gamma_1}{Q} = k m \frac{\Gamma_2}{Q} - (1 - k) \mu + (1 - k) \frac{\pi}{2} \lambda \kappa_0 \tag{11}
\]

where \( \mu = \frac{\operatorname{ctg} \beta_{02}}{\Delta_2} = 2\pi r_2 B' \operatorname{ctg} \beta_{02} \) is the hydrodynamic parameter of the spatial lattice, which characterizes the direction of flow in relative motion, at which the hydraulic moment on the lattice is equal to zero;

\[
\lambda = \frac{r_2^2}{R^2} \text{ - dimensionless active lattice radius;}
\]

\[
\Delta_2 = \frac{1}{2} 2\pi r_2 B' \text{ is the thickness of the flow layer of the elementary lattice in the output section of the runner.}
\]

The above equations describe the kinematics of the flow in absolute and relative motion at the inlet and outlet of the runner lattice and can be used to analyze the water passage flow of a reversible hydraulic machine. These equations are used to calculate certain types of energy losses in elementary lattices that make up the spatial lattice of the runner of a reversible hydraulic machine.

### 3. Dimensionless Theoretical Characteristics of the Runner Elementary Lattice

The most important parameters characterizing the interaction of the fluid flow with the runner of a reversible hydraulic machine are the hydraulic torque relative to the axis of rotation and the hydraulic power given by the fluid to the runner.

The equations of dimensionless pressure, moment, and power characteristics, respectively, for the elementary lattice of the runner in a dimensionless form were used. \( \rho, D \) and \( Q \) [8, 9]: \( k_{ht}, k_{mt}, k_{mt} \) are taken as variables with independent dimensions.

To study the working process, it is also advisable to use another version of dimensionless complexes, where \( \rho, \omega, D \): \( k_{ht}, k_{mt}, k_{mt} \) [9-10] are taken as variables with independent dimensions.


According to the calculated parameters of elementary lattices, using the averaging formulas given in [12-13], the parameters of the spatial lattice of the runner are found.

For each of the elementary lattices of the runner, the constraint equation of circulation (1) is valid.
Multiplying both sides of the equation by $\frac{dQ}{Q}$ and integrating over all elementary lattices, to find:

$$\Gamma_2 = k_a \Gamma_1 - (1 - k_m) q \text{ctg} \beta_{n0} + (1 - k_m) 2\pi r'_0 \omega_0,$$

(12)

where

$$\bar{q} = \frac{1}{Q_0} \int qdQ = \frac{Q}{\Delta_2}, \quad \text{ctg} \beta_{n0} = \frac{1}{\Delta_2} \int \frac{q \text{ctg} \beta_{n0} dQ}{Q}.$$

$$\frac{r'_2}{R^2} = \frac{1}{Q_0} \int \left( \frac{r_n}{R} \right)^2 dQ.$$

$$\Lambda = \frac{r'_2}{R^2} = \sqrt{\frac{1}{Q_0} \int \left( \frac{r_n}{R} \right)^2 dQ}.$$

(13)

$$\mu = \frac{\text{ctg} \beta_{n0} D}{\Delta_2} = \frac{D \int q \text{ctg} \beta_{n0} dQ}{Q^2}.$$

If $q = \frac{\Delta_2}{Q_0} = 2\pi r_C 2\pi = 2\pi r_B_2 Q, B'_2 = B_2 D^2$ then:

$$\bar{\mu} = \frac{2\pi}{Q_0} \int r'_2 B'_2 \text{ctg} \beta_{n0} dQ. \quad \bar{\Lambda}'_2 = \frac{\bar{\Lambda}}{D} = \frac{Q}{2\pi \int r'_2 \beta'_2 dQ}.$$

When the blade system of the runner is divided into $n$ elementary lattices, the formulas for determining the hydrodynamic parameters of the runner spatial lattice can be converted to a form convenient for calculations:

$$\Lambda^2 = \sum_{i=1}^{n} \left( \frac{r'_i}{R^2} \right), \quad \bar{\Lambda}'_2 = \frac{\sum_{i=1}^{n} r'_i B'_i}{\Delta'_2}, \quad B'_2 = \frac{1}{2\pi \Lambda'_2 r_i}.$$

5. Relationship of the Hydrodynamic Parameters of Elementary Lattices with the Spatial Lattice of Runner

Fig. 1 shows straight lines $\frac{r'_2}{n_i} = f \left( k'_0 \right)$ at $\left( \frac{\Gamma'_2 D}{Q} \right)_{\text{op}} = \text{const}$, for three lattices (bushed, middle, peripheral) corresponding to the theoretical dependence $\frac{r'_2}{n_i} = \frac{\pi}{60} \lambda - \frac{\pi}{30} \mu k'_0$, as well as experimental data of a spatial lattice for a reversible hydraulic machine: ORO200.

![Figure 1: Dependencies $\frac{r'_2}{n} = f \left( k'_0 \right)$ and $\eta = f \left( k'_0 \right)$ for runner elementary lattices of the ORO200](image)
Calculated value of $K_{mT}$ at the optimal mode is approximately the same for all elementary lattices and is in good agreement with the value obtained from the experimental data (Fig. 1).

Fig. 2 shows the dependencies $\frac{\Gamma_D}{Q} = f(k_o)$ and $\eta = f(k_o)$ for ORO200. Dependence analysis shows that all lattices have a small positive swirl near the mode of the corresponding efficiency maximum (at $\frac{\Gamma_D}{Q} = const \{ a_0 = const \}$).

Figure 2: Dependencies $\frac{\Gamma_D}{Q} = f(k_o)$ and $\eta = f(k_o)$ for runner elementary lattices of the ORO200

An analysis of the dependences of the loss coefficient of the runner with high energy performance (Fig. 3) shows that the nature and the minimum of the loss coefficients dependences of the three elementary lattices are almost the same. This indicates a fairly good agreement between the runner elementary lattices among themselves (i.e., the optimal mode is the same for all lattices). It was possible to obtain high energy performance of the reversible hydraulic machine.

Special attention was paid to the flow around the runner blades. The following features of the flow in a high-pressure reversible hydraulic machine were noted when it was operated in the turbine mode at optimal values of the reduced flow rate and speed.

The flow in the runner has a complex nature. The change in pressure during the transition from the wicket gate area to the runner area is in Fig. 5. As can be seen from the figure, the pressure in the runner lattices gradually decreases until the exit from the runner.

Figure 3: Dependencies $K_{mT} = f(k_o)$ and $\eta = f(k_o)$ for runner elementary lattices of the ORO200

Numerical research was carried out on the optimal turbine operating mode of the reversible hydraulic machine. The graph shows that the curves corresponding to 0.5 b and 0.9 b have a sufficiently smooth character. Curve 0.1 b shows uneven pressure distribution.

The distribution of the velocity components at the exit from the runner is on Fig. 7.

It can be seen from the figure that the speed value for the runner in the middle of the channel is almost two times higher than near the ages. The value of the absolute velocity varies smoothly along the height of the channel, and the value of the relative velocity varies smoothly enough. The nature of the curves indicates that the profiled blade has a good geometry.

These characteristics indicate that there is a small positive swirl behind the runner (Fig. 8), which was also noted during the mathematical study of the ORO200 blade system [11, 14-15].

This confirms the adequacy of the selection of initial parameters when designing high-head reversible hydraulic machines.

6. Conclusions

Applying equations that describe the kinematics of the flow in absolute and relative motion at the inlet and outlet of the runner for calculation and analysis of the hydrodynamic characteristics of elementary lattices makes it possible to evaluate their influence on the runner of a reversible hydraulic machine and to assess the degree of consistency of elementary lattices that make up the runner spatial lattice.

Using the regularities of changes in the hydrodynamic characteristics of elementary lattices makes it possible to determine the loss coefficient of the runner in the optimal mode of operation and to evaluate the consistency of the runner elementary lattices with each other.

The results of numerical modeling of the 3D model of the ORO200 runner showed the adequacy of the application methods for calculating the hydrodynamic and energy characteristics of the runner. As a result of this was possible to obtain high-energy performance of the reversible hydraulic machine.
References


[3] Energy Strategy of Ukraine for the period up to 2035, approved by the Order of the Cabinet of Ministers of Ukraine dated August 18, 2017 No. 605


